A Fugue on Rumination

On the Dynamic Nature of Rumination's Key Features and Their Complex Interplay with Executive Control

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Résumé

Cette thèse reconceptualise les ruminations mentales comme un construit dynamique et multifacette, remettant en cause la représentation unitaire et statique classiquement faite de ce construit. Nous avons utilisé des méthodes expérimentales et longitudinales intensives pour étudier les fluctuations temporelles des ruminations et leur relation complexe avec le contrôle exécutif, un mécanisme clé supposé. Les résultats indiquent que la négativité des pensées alimente les ruminations, tandis que d'autres aspects (e.g., la répétitivité) semblent découler de défaillances de régulation de buts. Et, alors que les ruminations perturbent le contrôle exécutif, l'inverse n’est pas le cas : un contrôle exécutif affaibli ne favorise pas les ruminations. Ce travail appelle à une réévaluation des théories dominantes, suggère des raffinements méthodologiques, et encourage l’utilisation d’études longitudinales intensives et de modélisations multivariées pour saisir la dynamique de processus mentaux.

Abstract

This thesis reconceptualizes rumination as a dynamic, multifaceted construct, challenging its predominant portrayal as unitary and static in mental health research. We used experimental and intensive longitudinal methods to investigate rumination’s temporal fluctuations and intricate relationship with executive control, a key hypothesized mechanism. Results suggested that negative thought content drove rumination, whereas other features (e.g., repetitiveness) seemed to stem from goal-regulation failures. And, while rumination disrupted executive control, the reverse was not found: weakened executive control was not related to increased rumination. This work calls for a re-evaluation of prevailing theories, suggests methodological refinements, and advocates for intensive longitudinal research and multivariate modeling to capture the intricate dynamics of mental processes.

Table of Contents

Acknowledgements

In the book “The Unfair Advantage” by Ash Ali and Hasan Kubba, the authors talk about “unfair” advantages. These are anything that put you in a favorable position to succeed in life, such as being born in a Western country, benefiting from a large financial inheritance, or being tall in basketball. This book provides the reader with a framework to think about their life and about aspects of their life beyond their control for which they can be grateful. Upon reading this book and thinking about the five and a half years of my PhD, it struck me that, without a doubt, the people who surrounded me and those I met during these years were one of my biggest unfair advantages.

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Foreword

A fugue is a musical composition characterized by a short melody or phrase (referred to as the theme or the subject) that is introduced at the beginning of a composition. The subject is then repeated, imitated, and developed by other voices (i.e., instruments or parallel melodies), creating a complex structure by interweaving the various parts. It is a complex style of composition that usually has three main sections: an exposition, a development, and a final entry. The exposition serves to present the subject of the fugue and introduce the different voices. The development is the part during which the compositor has the most freedom though it still follows a logical structure wherein the subject can be explored in different ways. And the final entry is the closing section of the fugue.

When searching for a title for my dissertation, I thought a 'fugue' was a perfect metaphor to illustrate and represent my doctoral dissertation. Indeed, my dissertation includes different moving parts, theories, methodologies, analytical frameworks, and study designs. However, it is all related to a central subject and goal: to achieve a better understanding of the associations between rumination and executive control. Moreover, in the same way a composer can have a specific affinity towards a melody he composed or stumbled upon, or affinity towards certain instruments, I had a particular affinity towards better understanding rumination. And, as time is a limited commodity, we could not do everything Alexandre, my supervisor, and I had planned. Faced with the ebbs and flows of life (e.g., unforeseen events such as a pandemic lasting two years and some health issues), we had to improvise and adapt. We thus moved towards what seemed to make the most sense regarding the questions that interested us and what motivated me.

The result is a dissertation in which the central subject, "How can we advance our understanding of the associations between rumination and executive control?" is taken up by different chapters from different angles: a systematic review, an experimental study based on the systematic review, a validation of a rumination measure, and extended data analysis of intensive longitudinal data in three chapters. In the introduction, the reader will notice that, in our attempt to answer the central question of this Ph.D. thesis, the measurement, conceptualization, and temporal nature of rumination took a central role. We argue that better understanding, conceptualizing, and measuring rumination is key for the field to move forward.

In the end, this dissertation discusses more the conceptualization and measurement of rumination than the conceptualization and measurement of executive control. Additionally, it discusses how changing how we measure and conceptualize rumination can influence the associations with executive control we can uncover. Beyond investigating the associations between rumination and executive control, I also had the opportunity to explore the use and utility of various computational frameworks, each with its advantages and weaknesses.

In summary, in the same way a fugue is a complex composition with a central subject and interwoven parts, my dissertation forms a whole in which the central subject is approached from different angles, creating complexity through the number of moving parts. In the discussion, much like the fugue that reaches a climax and an end, I hope the reader will find a satisfactory climax and ending that tie together and extends our results, highlighting the implications for future research and leaving the path open for other researchers to follow-up on the melody.

Introduction

In the intricate symphony of the mind, understanding the origins and implications of a mental process like rumination is akin to dissecting the essence of a fugue played by an orchestra. Is it the conductor's baton, the musicians' expertise, the composer's vision, or the intrinsic qualities of the music and sound itself that breathe life into a fugue? Similarly, when considering the phenomenon of rumination, do we attribute its existence to the various features of thought, the interplay of cognitive processes, or the broader context of one's life situation? Just as we have a consensus on what a fugue is in musical terms, defining rumination is within reach, yet understanding its intricacies is substantially more complex.

In the first chapters of this thesis, we delve into the theoretical background necessary for understanding how rumination has been defined and studied. We focus on a specific hypothesized mechanism involved in rumination, namely executive control. These first chapters will highlight that, despite considerable progress in understanding rumination in the last two decades, the intricate mechanisms underlying rumination remain uncertain. We argue that this uncertainty may stem from a unitary conceptualization of rumination and a lack of research into its temporal fluctuations. These limitations are discussed in Chapter 3, with further exploration and proposed solutions in Chapters 4 and 5.

This thesis aims to address these two limitations by reconceptualizing rumination as a dynamic, multifaceted construct, and investigate its relationship with executive control. The threefold objectives are to conceptualize and study rumination as a construct comprising multiple interacting features that vary over time, examine the interplay between specific features of rumination and executive control, and elucidate theoretical, methodological, and clinical implications from this refined perspective on rumination.

Section 1.

Theoretical background & thesis objectives

Chapter 1.

Models of rumination

We all think constantly. We might think about our work, what we will eat at lunch, the new movie we want to watch at the cinema this weekend, or a holiday trip we excitingly await. Yet, just like how “the world ain’t all sunshine and rainbows” (Stallone, 2006), neither are our thoughts. Sometimes our thoughts take a negative turn. For example, we might think about an argument we had with a friend and how we wish we had said things differently. In such cases, thoughts quickly become repetitive as we investigate different scenarios: we might think of better arguments, a joke that could have lightened the mood, or perhaps we think of a way we could have avoided this argument altogether. Sometimes, thinking about one negative event might lead us to think about other negative themes (e.g., “Why can’t I control my emotions better?”). Such thoughts often persist, filling up the available time until something requires our immediate attention.

Psychologists refer to such repetitive, negative, self-focused thoughts as *rumination*. Although it is something humans do naturally, it is not beneficial per se. Indeed, when done in excess, rumination might perpetuate and cause lasting negative emotions and mood and impede other activities (e.g., work or sleep). Unsurprisingly, researchers observed elevated levels of rumination in depression and other mental health issues such as general anxiety, bipolar disorder, post-traumatic stress disorder, and eating disorders (K. J. Hsu et al., 2015; Moulds et al., 2020; Silveira Junior & Kauer-Sant’Anna, 2015; K. E. Smith et al., 2018).

> The happiness of your life depends upon the quality of your thoughts.
> (Aurelius, 1726, p. 155)

It is ancient wisdom that perseverative negative thinking leads to detrimental outcomes and that the quality of our thoughts shapes our lives. Yet, one might wonder, “*How exactly* does it shape our lives?” To answer such a question, we must first better understand our thoughts.

Rumination is omnipresent in our daily lives and impacts ourselves and the people around us. It is therefore no surprise that rumination has been extensively studied over the past decades as psychologists and researchers strived to better understand it. As a result, researchers developed several theories about rumination. In this section, I will present and summarize the main models of rumination.

1.1 The Response Styles Theory

One of the most prominent theories of rumination is the Response Styles Theory (Nolen-Hoeksema et al., 2008), which conceptualizes rumination as a learned habitual tendency. Response Styles Theory (RST) initially arose from Nolen-Hoeksema's desire to better understand the gender differences in depression: why did more women than men seem to suffer from depression? She found that women's reliance on rumination as an emotion regulation strategy explained gender differences (Nolen-Hoeksema, 1987). In contrast, men tended to engage more in distraction when faced with a negative mood. Hence, women's preferred emotion regulation style exacerbates their negative mood, whereas men's main coping style reduces negative moods (Nolen-Hoeksema & Morrow, 1993). Moreover, being faced with more uncontrollable and chronic stressors might lead to rumination (e.g., Nolen-Hoeksema & Davis, 1999; Nolen-Hoeksema & Jackson, 2001; Watkins & Nolen-Hoeksema, 2014). Consecutively, through a downward spiral between chronic stress and rumination reinforcing each other, rumination might become a habitual style of dealing with negative affect. Hence, in her work, Susan Nolen-Hoeksema emphasized that the impact of rumination on depressive mood does not differ between women and men (Rood et al., 2009). Instead, she found that women are more likely to suffer from depressive episodes because they have a higher tendency to use rumination to deal with negative affect (Nolen-Hoeksema et al., 1999), which might be a gender difference induced by different beliefs regarding emotions and "differences in chronic strain, histories of abuse, and other contextual factors" (Nolen-Hoeksema & Jackson, 2001, p. 46).

Moving beyond gender differences in depression, Susan Nolen-Hoeksema aspired to clarify the relationship between rumination and depression and developed the Response Styles Theory (RST). The RST conceptualizes rumination as a maladaptive style of regulating emotions and mood. According to the RST, rumination consists of a stable and habitual tendency to engage in repetitive negative thoughts focused on one-self, that is, repetitive and passive thoughts about one's experiences and their potential causes and consequences. Moreover, people that ruminate do not take any problem-solving actions to change the circumstances surrounding these symptoms (Nolen-Hoeksema, 1991; Nolen-Hoeksema et al., 2008). Importantly, RST highlights the repetitive and passive nature of ruminative thoughts rather than defining rumination just by the negative content of thoughts (Nolen-Hoeksema, 1991).

According to the RST, people engage in depressive rumination because they think it might help them better understand their depressive state and symptoms. Yet, rather than leading to better self-understanding, rumination (1) impairs problem-solving, (2) interferes with instrumental behavior, (3) enhances negative mood-congruent thinking, and (4) reduces social support (Lyubomirsky et al., 2015; Lyubomirsky & Nolen-Hoeksema, 1993; Nolen-Hoeksema, 1991; Nolen-Hoeksema et al., 2008). Moreover, the RST hypothesized that rumination would be associated with the onset and maintenance of depression. The association between rumination and the onset of depression has been well documented (Abela & Hankin, 2011; Just & Alloy, 1997; Nolen-Hoeksema, 2000). The association with the duration of depressive episodes, however, has not been consistent in the literature (Ciesla & Roberts, 2002; Just & Alloy, 1997;

Kuehner & Weber, 1999; Nolen-Hoeksema, 2000; Robinson & Alloy, 2003): rumination is associated with depression duration "only to the extent that [thoughts] are negatively biased and irrational" (Lyubomirsky et al., 2015, p. 10).

In summary, the RST considers rumination a learned tendency to engage in repetitive self-focused thoughts. It does not explain why rumination might vary depending on the context, nor why some people might ruminate in one situation compared to another. Hence, RST is a widely used theory that describes depressive rumination and explains individual differences as different learned trait tendencies. However, it also has limitations, as it fails to describe the ruminative process in much detail.

Although the Response Styles Theory is the most widely used theory and the Ruminative Response Scale (Treynor et al., 2003) is the most widely used measure of rumination, other theories of rumination exist. These theories complement and extend Nolen-Hoeksema's conceptualization of rumination.

1.2 The Goal Progress Theory of rumination

Whereas the RST puts forward the role of mood in the onset of rumination, other models put forward the role of goals and goal discrepancies. For instance, the Goal Progress Theory (also referred to as the 'control theory' of rumination) defines rumination as "a class of conscious thoughts that revolve around a common instrumental theme and that recur in the absence of immediate environmental demands requiring the thoughts" (Martin & Tesser, 1996a, p. 1). This model posits that rumination arises as a response to unsatisfactory goal progress or as a response to a threat to progress towards a goal. The process can be summarized as follows: a slower-than-expected perceived progress towards a desired goal triggers rumination; the person will then continue engaging in rumination until (real or perceived) progress to reduce the goal discrepancy is made, the goal is attained, or until the person disengages from the goal. Hence, Martin and Tesser (1989) specify that rumination will recur in the absence of immediate demands requiring one's thoughts.

The function of rumination, according to the Goal Progress Theory, is to gain awareness of unsatisfactory goal progress and to facilitate progress towards an unattained goal. Therefore, based on this model, rumination is not maladaptive per se. As rumination highlights a goal discrepancy, it can be adaptive if it helps reduce the perceived discrepancy by promoting progress towards the goal (Andrews & Thomson, 2009; Bartoskova et al., 2018; Watson & Andrews, 2002). However, when rumination fails to help make satisfactory progress towards a goal or when the person fails to disengage from the goal, rumination is maladaptive: it causes recurring thoughts about the failure to make progress towards the activated goal, which in turn intensifies negative affect (Carver, 1996; Moberly & Watkins, 2008; Watkins, 2008).

In a subsequent paper, Martin & Tesser extended their framework in several ways (Martin & Tesser, 2006). First, they discussed how the simultaneous pursuit of multiple goals influences rumination: if progress towards one goal facilitates progress towards other goals, people will be less likely to ruminate; but if progress towards one goal interferes with making progress towards other goals, it will likely lead to increased rumination. Second, they addressed how rumination can be driven by higher-order goals (e.g., "Be creative.") and the implications of when a person pursues goals that are not congruent with their needs and values (e.g., Sheldon & Kasser, 2001). Third, although they did mention that people could stop ruminating by disengaging from goals in previous writings, they did not specify how; hence, they further described this process. Lastly, they expanded their framework to be able to describe how traumatic experiences lead people to sometimes reevaluate their goals and come out of the traumatic experience better overall.

The strength of this model is that it provides a proximal causal mechanism to understand state rumination: it describes conditions that lead to rumination and the cognitions that maintain it. However, the Goal Progress Theory fails to explain how different people will have different tendencies to ruminate (i.e., trait rumination) beyond goal characteristics, nor does it explain why rumination can be present in the absence of current or perceived failure (see Nolen-Hoeksema & Morrow, 1991; Spasojević & Alloy, 2001). Note that Martin and Tesser only attempted to specify what the general process of rumination is, which does not mean they did not expect to observe interindividual differences (cf., Martin & Tesser, 1996a). Lastly, this theory is compatible with the Response Styles Theory, as depressive mood and stressful life events may be considered as consequences of failed/blocked goals or lack of progress towards goals (Manigault & Zoccola, 2020).

1.3 The Habit-Goal framework

The Response Styles Theory focuses on interindividual differences linked to rumination and how these can predict depressive episodes (Nolen-Hoeksema et al., 2008). In contrast, the Goal Progress Theory of rumination focuses on the state occurrence of rumination as a goal-oriented type of thinking (Martin & Tesser, 1989, 1996a). The Habit-Goal framework, proposed by Watkins and Nolen-Hoeksema (2014), reconciles these two perspectives. This framework relies on the conceptualization of rumination as a mental habit (Hertel, 2004) connecting the ideas of habits and goals using Wood & Neal's (2007) theoretical framework.

Habits are established through repeated pairing between a stimulus and a response (Dickinson & Weiskrantz, 1985) or, in other words, "as a result of frequent covariation of the behavior with the cueing context" (Watkins & Nolen-Hoeksema, 2014, p. 25). They are learned dispositions to respond to cues in accordance with past responses (Wood & Neal, 2007). Habits also have a certain degree of automaticity. Hence, rumination, often characterized as repetitive, unintentional, and even uncontrollable (Watkins & Baracaia, 2001), perfectly aligns with the definition of 'habit.' Moreover, Hertel (2004) conceptualized rumination as a habit of thought as it is often initiated without conscious awareness or intent.

According to Wood and Neal (2007, p. 844), "habits typically are the residue of past goal pursuit: they arise when people repeatedly use a particular behavioral means in particular contexts to pursue their goals." Based on this, Watkins and Nolen-Hoeksema (2014) argue that rumination is a goal-directed behavior (cf., Martin & Tesser, 1996a) that could become a habitual response if it repeatedly occurs in response to a specific context (which can include stimuli related to the time of the day, internal states, surroundings, people, etc.). For instance, this is how rumination can become associated with and triggered by negative mood, consistent with the Response Styles Theory. Importantly, the more various responses are used in a specific context, the less likely any specific response will develop into a habit triggered by that specific context: "The greater the numbers of behaviors linked to a given context, the lesser the capacity for the context to cue any one behavior directly" (Wood & Neal, 2007, p. 858). Hence, if, for instance, people are used to using various emotion regulation strategies such as problem-solving and distraction, rumination will have a lower probability of becoming a habitual response. This explains why people can experience ruminative episodes without necessarily developing a habitual ruminative response tendency.

The second idea of Wood and Neal's (2007) framework for understanding habits is that context-response associations are not mediated by goal activation. This means that a habitual ruminative response "would be triggered by the relevant cueing context (e.g., negative mood) in the absence of a personally important unresolved goal or of an intention to think about the related concern" (Watkins & Nolen-Hoeksema, 2014, p. 28). This explains how rumination can be triggered without intention or effort.

The third and last idea of Wood and Neal (2007) that can be applied to better understand rumination is that habits are resistant to change. More precisely, "habits arise from context–response learning that is acquired slowly with experience. As a result, habit dispositions do not alter in response to people's current goals or occasional counter-habitual responses" (Wood & Neal, 2007, p. 844). According to Watkins and Nolen-Hoeksema (2014), this key characteristic of habits is one reason rumination can be so persistent, difficult to stop once it starts, and difficult to treat and replace by alternative, more adaptive thinking patterns.

By combining the Response Styles Theory and the Goal-Progress Theory, the Habit-Goal framework can account for both state rumination and trait rumination. Based on this framework, state rumination, which refers to rumination as it occurs, can be triggered by goal discrepancies but also by habitual ruminative thoughts in response to previously conditioned triggers such as low mood. In contrast, trait rumination which refers to the broad tendency to ruminate, can arise from different underlying mechanisms: someone might have ruminated a lot in the last few weeks because they faced a lot of adverse events (i.e., situations leading to unresolved goal discrepancies) or because rumination is a habitual type of thinking style for them, even in the absence of unresolved goal discrepancies. Therefore, rumination can occur both as a situational response and as a consistent pattern of thinking, with these two aspects interacting in complex ways.

In summary, the Habit-Goal framework for rumination integrates the goal-progress model (Martin & Tesser, 1996a), which explains best state rumination, with the Response Styles Theory (Nolen-Hoeksema et al., 2008), which conceptualizes rumination as a habitual style of thinking. According to this framework, people can experience ruminative episodes (e.g., triggered by goal discrepancies) without necessarily developing a habitual ruminative thinking tendency. It is only to the extent that the ruminative response is associated repeatedly with a specific context that rumination could become a habitual response when this context is cued in the absence of goal discrepancies. Watkins and Nolen-Hoeksema's (2014) framework also illustrates how rumination might be a hard habit to break once it has become established. Indeed, with some of its triggers being internal (e.g., negative mood), it can be hard to use typical strategies used to modify habits, such as stimulus and environmental control (Watkins & Nolen-Hoeksema, 2014). Moreover, self-control is typically required to generate nonhabitual responses needed to break habits, but some results indicate that rumination might reduce people's ability to exert self-control (e.g., Curci et al., 2013; Watkins & Brown, 2002). It is also possible that existing impairments in self-control abilities (operationalized and further described in section 1.4.) may lead to sustained rumination.

1.4 Models associating rumination and executive control

Executive control (also called 'cognitive control' or 'attention control') is an umbrella term that refers to high-level, complex processes that allow individuals to efficiently organize and regulate a series of cognitive processes (Baddeley, 1992; Norman & Shallice, 1986) depending on the situation and their goals (Miller & Cohen, 2001). Such top-down processes are crucial to our everyday lives as they are the backbone of our ability to pursue goals and self-regulate thoughts and actions. These executive control processes allow us to navigate through various activities: for instance, tasks that require decision-making, complex cognitive operations, conflict resolution, and overriding habitual responses. Given that executive control is thought to regulate both our behaviors and our thoughts, it is not surprising that rumination has been linked to executive control in several models. These models propose that executive control is an important process to consider in order to understand rumination.

For instance, executive control plays an important role within the **Self-Regulatory Executive Function** (**S-REF**) model (Matthews & Wells, 2004; Wells & Matthews, 1996). In this model, executive control abilities are comprised within a "supervisory executive system". The supervisory executive system's role is to monitor any motivationally relevant stimuli (i.e., external and internal stimuli) and to implement strategies to reduce any discrepancy between a current state and the desired state. The supervisory executive system will appraise the situation, select and implement coping strategies, and monitor their implementation. In this model, the authors emphasize the role of metacognition and how it influences executive control. Metacognitive beliefs specify "(1) the personal significance and (2) the coping implications of thoughts" (Matthews & Wells, 2004, p. 129). These metacognitive beliefs bias the appraisal, the choice of coping strategy, and the monitoring made by the supervisory executive system. For instance, if a person believes that thinking about a situation and replaying it in their mind might be beneficial and helpful, that person will more likely engage in rumination as a preferred coping strategy. And a metacognitive belief that specifies that if "I still feel bad about a situation, it is because I have not thought about it enough" might lead a person to continue to ruminate despite its ineffectiveness at improving the situation. From the perspective of the S-REF model, rumination "derives in part from the person's metacognitive beliefs that specify the use of rumination as a strategy for coping and self-regulation." (Matthews & Wells, 2004, p. 130). Hence, executive control is necessary to implement volitional rumination, and the self-regulation made possible by executive control can be biased by metacognitive beliefs.

Another set of models, which can be referred to as the **resource depletion account or resource allocation hypothesis** of rumination, postulate that rumination occupies cognitive resources that are therefore not available for other concurrent tasks (Beevers, 2005; Hartlage et al., 1993; Hertel, 2004; Kofta & Sedek, 1998; Levens et al., 2009). In other words, these models hypothesize that rumination, through the monopolization of cognitive resources, interferes with concurrent executive processing and effective resource allocation, which translates to impaired performance on a wide range of tasks (Brinker, 2013; Philippot & Brutoux, 2008; Watkins & Brown, 2002). Although a few studies found results supporting the resource depletion account, it has not been extensively researched.

Lastly, the **impaired disengagement hypothesis** is a model that attempts to explain the relationship between difficulties in disengaging from negative content, such as negative thoughts, and rumination (Joormann, 2010; Koster et al., 2011). It posits that deficits in executive control (referred to by Koster and colleagues as 'attentional control') create difficulties in discarding no longer relevant information from working memory and that, consequently, negative thoughts can proliferate, leading to prolonged rumination. According to the impaired disengagement hypothesis, a perfect example of the interplay between executive control and rumination is depression. It has been shown that people suffering from depression have impaired executive control, which is associated with a higher tendency to ruminate, but mostly in severely depressed individuals (Joormann et al., 2007). Indeed, in healthy individuals, self-critical, negative thoughts are typically not congruent with their positive self-views. Hence, when faced with negative thoughts, people will experience cognitive conflict. Healthy individuals will disengage their attention from these negative thoughts (e.g., Mauss et al., 2007). As Koster et al. (2011) put it in their theoretical paper, "Successful disengagement of attention from negative thoughts then allows to reappraise the situation or distract from the situation altogether by focusing attention on other (task-relevant) stimuli or more positive distracters." (p. 140). However, depressive individuals with impaired executive control would not be able to disengage from negative thoughts, which could be an explanation of why rumination is such a central symptom of depression.

Several researchers also note the possibility that the relationship between rumination and impaired executive control is bi-directional (e.g., De Raedt & Koster, 2010; Denson, 2013; Hartlage et al., 1993; Hertel, 2004; Joormann et al., 2007). For instance, Hertel (2004) suggests that (a) impaired executive control can help habit emerge as poorer executive control may interfere with the ability to override response tendencies, and that (b) habitual rumination occupies cognitive resources which are therefore unavailable for other tasks. Additionally, Denson (2013) created the Multiple Systems Model, which hypothesizes a bidirectional relation between executive control and anger rumination (i.e., rumination about an anger-generating event): impaired executive control contributes to the onset of anger rumination after an anger-generating event; anger rumination, on the other hand, temporarily reduces executive control, which can facilitate aggressive behavior. In summary, rumination could be both a consequence and a cause of poor executive control.

These models provide a framework for understanding the cognitive processes underlying rumination. Building upon these models, an ever-growing number of studies on the associations between rumination and executive control get published every year. One can find no less than three meta-analyses investigating the associations between rumination and executive control (du Pont et al., 2019; Yang et al., 2017; Zetsche et al., 2018). They all find some support for significant associations between rumination and executive control, but they all relied almost solely on cross-sectional research. The direction of causality between increased rumination and impaired executive control remains therefore unclear. However, whereas only a handful of studies investigated whether rumination impairs executive control (e.g., Brinker, 2013; Philippot & Brutoux, 2008), the majority of interventional and experimental studies have investigated whether improving executive control leads to reduced rumination: for example, executive control training studies (Cohen et al., 2015; Hoorelbeke, Van den Bergh, et al., 2022), neurofeedback training (e.g., Enriquez-Geppert et al., 2013; Yu et al., 2020), and neuromodulation studies (e.g., De Putter et al., 2015; Vanderhasselt et al., 2015). Although some results find that improved executive control is associated with reduced rumination, there is a high heterogeneity in the studies and results.

In summary, executive control does seem to be an important process involved in rumination based on theoretical models and empirical research. However, most results come from cross-sectional studies. Moreover, the literature is biased towards studying one direction of causation (i.e., worse executive control causes increased rumination) at the expense of the opposite direction of causation. Chapter 2 will review this literature in detail.

1.5 The HEXAGON model

With the great advances made in the understanding of rumination over the last decades, there was a need for models that integrate the various bouts of research. In 2020, while this thesis was in its second year, Watkins and Roberts (2020) performed such an integrative review of the literature. They presented a theoretical framework comprising five interacting mechanisms of rumination: **H**abit development, **EX**ecutive control, **A**bstract processing, **GO**al discrepancies and **N**egative bias—the H-EXA-GO-N model. This model synthesizes multiple prior models each explaining specific aspects of rumination, some of which have already been presented whereas others will be described: Response Styles Theory (Nolen-Hoeksema et al., 2008); Goal-Progress Theory (Martin & Tesser, 1996b); Conceptual evaluative vs concrete-experiential (Watkins, 2008); Habit-Goal framework (Watkins & Nolen-Hoeksema, 2014); impaired disengagement hypothesis (Koster et al., 2011).

The two core proximal explanatory mechanisms of the HEXAGON model are the goal-progress mechanism and the habit-development of rumination. On the one hand, as we have discussed previously, the goal-progress mechanism allows to explain state rumination (i.e., rumination as it occurs) as rumination and other types of repetitive cognition get triggered by threats to goals or discrepancies between current and targeted states. However, the goal-progress mechanism is not sufficient to make sense of people's tendency to ruminate (i.e., trait rumination) and how rumination can become habitual for some; it does not explain interindividual characteristics beyond differences in the characteristics of people's goals. On the other hand, the central assumption of the Response Styles Theory is that rumination is an automatic conditioned response to low mood (Watkins & Nolen-Hoeksema, 2014). Furthermore, rumination meets the definition of a habit as it occurs frequently, involuntarily, and repetitively in similar contexts (Verplanken, 2018; Verplanken et al., 2007; Wood & Neal, 2007). However, the Response Styles Theory does not explain acute episodes of rumination other than through habitual rumination being triggered by depressed mood.

As such, to best explain both state rumination and trait rumination within the same framework, Watkins and Nolen-Hoeksema (2014) integrated the goal discrepancies mechanism with a habit development mechanism. This goal-habit account postulates that initially rumination gets triggered as a response to goal discrepancies. Over time, rumination becomes a mental habit through the repeated use of rumination as a primary strategy to deal with goal discrepancies. Such development of a habit through repeated association of a response within a specific context (e.g., low mood) is in line with theories of habit formation (Verplanken, 2018; Wood & Neal, 2007).

An example of this for rumination could be a person that is either facing enduring adversity such as being bullied at school or facing repeated consecutive stressors (e.g., loss of close relatives, stress at work, relationship conflicts). In such a situation, acute rumination occurs initially due to a lack of progress towards meaningful goals. Then, if rumination is repeatedly used to deal with goal discrepancies (instead of other more adaptive emotion regulation strategies), the person will develop rumination-as-a-habit, through repeated association of rumination with e.g., negative emotions or negative mood. As Watkins and Roberts (2020, p. 127) put it : “This goal-habit approach can explain how state rumination can both be triggered by specific circumstances in all people and how trait rumination can develop in some individuals who have experienced the relevant setting and learning conditions.”

Watkins and Roberts (2020) extended the Habit-Goal framework by including a deficit in the application of executive control in the context of negative information as an additional mechanism (i.e., the impaired disengagement hypothesis; Koster et al., 2011). They specify that impaired executive control could influence rumination via (a) an inability to switch, disengage from, or update the information in working memory leading to the increased presence of negative information in working memory which translates in prolonged rumination, and (b) an inability to override habitual ruminative responses tendencies.

Two other mechanisms are the chosen processing style and negative bias. First, according to Watkins (2008) the type of processing style chosen by the person to think repetitively about negative information helps to explain why sometimes repetitive thoughts can be adaptive or maladaptive. In this way, it addresses limitations of both the Response Styles Theory, which focuses on maladaptive rumination and rumination as a failed attempt at problem-solving, and the Goal-Progress Theory, which considers rumination only as unhelpful if it does not address or resolve a goal discrepancy but does not operationalize unhelpful vs. helpful rumination. Watkins (2008) distinguished between two types of processing style. On the hand one, an abstract processing style that "involves general, superordinate, and decontextualized mental representations that convey the essential meaning, causes, and implications of goals and events (the "why" aspects of an action)" (Watkins & Roberts, 2020, p. 12). On the other hand, a more concrete processing style that "involves a focus on the direct, specific, and contextualized experience of an event. This processing mode addresses the details of goals, events, and actions that denote the feasibility, mechanics, and means of "how" to do the action" (Watkins & Roberts, 2020, p. 12). Several studies indicate that the abstract processing style is more maladaptive than the concrete processing style. For instance, prompting concrete thinking (e.g., "How are you deciding what to do next" (Watkins & Roberts, 2020)) compared to abstract rumination (e.g., "Why did this problem happen") improved problem-solving (Watkins & Baracaia, 2002; Watkins & Moulds, 2005), reduced negative self-judgments (Rimes & Watkins, 2005), and improved specificity of autobiographical memory recall (Watkins & Teasdale, 2001). More recent research, reviewed in Watkins & Roberts (2020), indicates that abstract rumination, compared to concrete rumination, has more negative consequences in respects to various mental disorders and contexts: (a) eating disorder (Rivière et al., 2018), (b) depression (Spinhoven et al., 2018), (c) PTSD (Schaich et al., 2013), etc. But the results are not always consistent as for instance, abstract rumination increased body dissatisfaction in women but concrete rumination increased body dissatisfaction in men (Rivière et al., 2018). The HEXAGON model posits that the chosen processing style—abstract versus concrete—either facilitates or impedes the reduction of goal discrepancies. Furthermore, this processing style may become habitual, such that individuals habitually engage in abstract processing when experiencing negative moods, thus contributing to the tendency to ruminate in a maladaptive way.

Second, negative information processing biases are also a key mechanism according to the HEXAGON model. These biases comprise the tendency to preferentially attend to negative information and delayed disengagement from negative information (i.e., attentional biases), negative interpretation biases (i.e., interpreting positive or ambiguous information negatively), and remember more negative information (Everaert et al., 2012). The literature reviewed by Watkins & Roberts (2020) offers mixed and limited support for the causal contribution of attentional bias to rumination. In contrast, the role of a negative interpretative bias and memory bias is better supported with studies indicating that it can influence both state (e.g., Hertel, Mor, et al., 2014) and trait rumination (e.g., Mor et al., 2014). This causal link is further supported by a recent trial that used cognitive bias modifications of interpretation (CBM-I) and found that the changes in interpretation bias partially mediated the effects of CBM-I training on rumination (Hirsch et al., 2018). Similar to processing styles, these biases can be understood as learnt tendencies, that is, habits, and that CBM-I training can change these interpretation habits (Hertel, Holmes, et al., 2014).

Importantly, the HEXAGON model considers that these five mechanisms contribute to the onset and maintenance of rumination in an additive and synergistic way, and are therefore not independent. According to the authors, the core mechanism is the formation of rumination as a habit, that is, when rumination is repeatedly used across multiple occasions and becomes a habitual response to the conditioned triggers. Moreover, the four other mechanisms then moderate this main causal route, by making rumination and its negative consequences more or less likely.

In summary, this model conceptualizes that the likelihood that a person ruminates at any point and the negative consequences of rumination will be a function of how habitual rumination is for them, their life circumstances, the processing mode they use, the extent to which they have negative interpretation and memory biases, and their executive control abilities. All these mechanisms interact at any time. Moreover, the model captures how environmental distal factors and biological distal factors contribute to rumination. However, it does not conceptualize how rumination is continuously affected by the biological factors and the biological changes induced by distal factors such as affected brain development due to stress, the autonomic nervous system (e.g., see research on heart rate variability), brain function (e.g., the role of the Default Mode Network), etc. For instance, the model does not discuss how the physiological consequences of rumination could be maintenance factors of rumination. Admittedly, creating a theory and model that accounts for all the variables would be like untying a Gordian Knot, but that means there is room for further theoretical progress in rumination.[1] In line with this statement, Watkins and Roberts emphasize that, although the model can account for both trait and state rumination, the understanding of the onset and maintenance of rumination and how all the mechanisms interact as rumination occurs (as a state) needs further research.

1.6 Other rumination models

1.6.1 Repetitive Negative Thinking

The previous sections did not aim at being exhaustive but instead focused on the most prominent and studied rumination theories. Yet, several other theories have been developed. Many of them have focused on the contents of the thoughts and on their transdiagnostic nature.

Indeed, as researchers realized that repetitive types of thoughts such as rumination, worrying, obsessions, etc., are present in several disorders, they realized that they could fit under the same umbrella of *repetitive negative thinking* (RNT) about past experiences, current concerns, or worries about the future (Ehring & Watkins, 2008; Harvey et al., 2004). The transdiagnostic view of RNT states that, across mental disorders, identical thought processes are applied to

[1] Additional small limitations are the missed opportunity to integrate with latest theories of emotion and emotion regulation and the fact that the hexagon shape used to "visualize" the associations between rumination and its core mechanisms has no use other than visually organizing the six variables and as a nice acronym. A more useful schematic version of the model should have instead better reflected the distinctions Watkins and Roberts make about distal factors, proximal causal factors, the consequences of rumination, and different levels of constructs (biological, neural, etc.), as the current schema seemingly puts all the mechanisms on the same level of importance.

disorder specific content and that it is important to distinguish the content and processes of RNT (Ehring & Watkins, 2008). For instance, worrying and rumination refer to different thought characteristics but the thinking process would be similar. According to Ehring and Watkins (2008), all types of repetitive negative thinking follow the same *thought process*: they are (a) repetitive, (b) passive or perceived as relatively uncontrollable, and (c) focused on negative content. In contrast, it is the content and context of the thoughts that differs between different types of RNT: past experiences, depressive symptoms, future events, etc. Importantly, the 'process' characteristics are still descriptive and do not refer to causal mechanisms.

Results from several studies supported this idea of a shared underlying process dimension of RNT. For instance, initial evidence showed that measures of rumination and worry are highly correlated and both are associated to similar extents with depression and anxiety (e.g., Siegle et al., 2004). Since then, many studies have replicated these results and found that RNT types shared a common dimension and similar associations (Arditte et al., 2016; D'Hudson & Saling, 2010; Hur et al., 2017; Klemanski et al., 2017; McEvoy et al., 2010, 2013; Spinhoven et al., 2015; Topper et al., 2014).

However, to the best of my knowledge, this RNT concept remained at a statistical and conceptual level: the idea of a common underlying process with different thought content is well supported but there have been no attempts so far at creating a theory that could explain why this is the case. Interestingly, Ehring and Watkins (2008) do mention the Goal-Progress theory (Martin & Tesser, 2006) and the presence of goal discrepancies as the underlying cognitive mechanism of RNT: "a goal–discrepancy theory can account for the differences in the content of RNT between different disorders: different disorders are characterized by different goals and concerns, which would be reflected in the nature of the RNT." (Ehring & Watkins, 2008, p. 200). However, there has been no further theoretical advancements in the conceptualization of RNT based on the goal-progress theory or other mechanisms involved in repetitive thought (e.g., interpretation bias, habit forming, executive control). Consecutively, there is no consensus as to how exactly RNT is conceptualized and measured (for a review, see Samtani & Moulds, 2017), as is illustrated by the differences between questionnaires specifically designed to measure RNT (Douilliez et al., 2014; Ehring et al., 2011; Verplanken, 2006). For example, the Perseverative Thinking Questionnaire (PTQ; Ehring et al., 2011) comprises five *process* characteristics: repetitiveness, intrusiveness, uncontrollability, as the core characteristics, and two additional features, unproductivity and the perceived use of mental capacity.

In summary, RNT is an umbrella concept that focuses on the shared process characteristics of different types of repetitive negative thinking such as rumination and worry. Moreover, RNT is transdiagnostic as these characteristics of repetitive thought are present in several disorders (e.g., Wahl et al., 2019). However, there is no consensus on which process characteristics matter most, with studies varying greatly in the characteristics they measure, and with no limits to the number of additional descriptive variables the RNT concept could comprise. Finally, the biggest limitation is that these process characteristics do not correspond to underlying mechanisms. Therefore, it is still unclear whether identical mechanisms underlie identical process characteristics.

1.6.2 Rumination and physiology: the perseverative cognition hypothesis

Rumination has also physiological consequences, as initially theorized in the Perseverative Cognition Hypothesis. This model helps to illustrate how rumination is a maladaptive emotion regulation strategy as it interferes with successful regulation and perpetuates physiological responses triggered by stress and negative emotions.

The perseverative cognition hypothesis posits that worry, rumination, and similar phenomena play an important role in somatic health, on top of the mental health effects that have been extensively studied. The crucial aspect these phenomena share is their repetitive nature. Rumination has been defined as repetitive negative thoughts involving self-referential information. Worry has been defined as a chain of negative and relatively uncontrollable thoughts and images. As described in the previous section, these phenomena and other phenomena have been described as repetitive thoughts (Ehring & Watkins, 2008). However, the perspective assumed by Brosschot et al. differs from this focus on the nature and the content that is repetitive and instead focuses on the somatic health consequences: "The core feature of these repetitive cognitions that is responsible for the effects on somatic health is that they contain cognitive representations of a psychological problem, a difficulty, a crisis, or, in other words, a stressor. To refer to this central shared feature, we suggest the term perseverative cognition. Thus, we define perseverative cognition as the repeated or chronic activation of the cognitive representation of one or more psychological stressors" (Brosschot et al., 2006, p. 114).

Brosschot et al. (2006) highlight pathways through which some events or coping/emotion regulation strategies have prolonged effects on physiology — in addition to the acute effect of stressors and the impact of discrete and singular goal directed strategies. Traditionally, coping strategies are viewed as moderators of the effect of a stressor on health. For example, coping strategies aim to reduce, eliminate, avoid a stressor, or change the meaning of a stressor. In contrast, perseverative cognition can best be viewed as a mediator, a pathway, through which the stressor exercises prolonged effects on the body. It does this by maintaining active a representational form of the stressor that continues to activate the body, akin to a prolonged state of action readiness for the individual, as conceptualized within the framework of prominent theories on emotion and cognition (Dalgleish & Power, 2000; Frijda, 1988; Lazarus, 1991). Hence, the pathogenic pathway of perseverative cognition, according to Brosschot et al. (2006), is not its short-term effects on a system — its *intensity* —, but its *duration* and the maladaptive emotion regulation and autonomic consequences associated with it. The Goal-Progress theory explained how perseverative cognition such as rumination is triggered by goal discrepancies: an awareness of a failure to make progress towards a goal or threat to the ability to attain a goal. Additionally, the perceived uncontrollability of a stressor can lead to rumination and worrying. Indeed, there would be no need to ruminate or worry if one believed in their ability to handle, to control, a stressor (Brosschot et al., 1998; Everson et al., 1996; Gebhardt & Brosschot, 2002). Hence, the hypothesis is that perseverative cognition sustains cognitive representations of stressors which sustains the associated physiological responses that, over time, lead to disease (Brosschot & Thayer, 1998; Linden et al., 1997; Olff, 1999). Furthermore, the link between prolonged physiological activity and risk of disease has been well documented (Borghi et al., 1986; Cole et al., 1999; Stewart & France, 2001; Treiber et al., 2001).

Many studies have investigated the association between perseverative cognition and somatic health; they had initially been reviewed by Brosschot et al. (2006). A recent meta-analysis of sixty studies investigated the relationship between perseverative cognition and five physiological parameters (Ottaviani et al., 2016): systolic blood pressure, diastolic blood pressure, heart rate, cortisol, and heart rate variability. The associations with heart rate variability (i.e., the variability of the time-intervals between consecutive heart beats) is especially interesting as heart rate variability (HRV) is "the result of the dynamic interplay between the fast acting parasympathetic nervous system and the relatively slower sympathetic nervous system" (Ottaviani et al., 2016, p. 233). The phasic reduction of HRV as a physiological response to stress (or its cognitive representation) is an adaptive response. Yet, when this response leads to chronic low levels of HRV, it is detrimental "as it activates a cascade of physiological defensive systems, which eventually facilitate physical wear and tear of the systems (i.e., allostatic load)" (Ottaviani et al., 2016, p. 233).

The other physiological parameters, heart rate, blood pressure, and cortisol, are also useful important indicators of overall physiological health. Chronic high heart rate frequency or chronic high levels of blood pressure is considered as an important risk factor in cardiovascular mortality and morbidity, and hypertension (Bromfield & Muntner, 2013; Tjugen et al., 2010). Regarding cortisol, it is implicated in the activation of hypothalamic—pituitary—adrenal axis. Chronic activation of this axis is linked with physiological and psychological disease states (Herman et al., 2016; McEwen, 1998; Milligan Armstrong et al., 2021; Raber, 1998).

In the meta-analysis of Ottaviani et al. (2016), perseverative cognition was significantly associated with higher systolic blood pressure ($g = .45$) and diastolic blood pressure ($g = .51$), higher heart rate ($g = .28$), cortisol ($g = .36$), and lower heart rate variability ($g = .15$) in experimental studies. And in correlational studies, perseverative cognition was significantly associated with higher heart rate ($g = .20$), cortisol ($g = .32$), and lower heart rate variability ($g = .27$) (Ottaviani et al., 2016). Interestingly, the type of perseverative cognition measure (trait vs state) moderated the associations with heart rate and heart rate variability[2] in experimental studies: only the associations with state rumination were significant. In contrast, in correlational studies, there was a significant correlation between lower heart rate variability and higher trait perseverative cognition.

It is important to note that this meta-analysis excluded studies with clinical samples for two reasons: first, according to the authors, there were too few studies that investigated psychopathology and concomitant physiological states; second, medication use is not well controlled for in studies with clinical samples—which is not negligible as there are proven effects of antidepressants on physiological responses such as heart rate and heart rate variability (Kemp et al., 2014). Although they found nine studies on clinical samples but did not include them in the meta-analysis, the results of these studies overall support the conclusions of this meta-

[2] Moderations with the cortisol and blood pressure could not be tested.

analysis, that is, the correlation/effect of perseverative cognition on the physiology (Aldao et al., 2013; Gilbert & Gruber, 2014; Halligan et al., 2006; Hofmann et al., 2010; Huffziger, Ebner-Priemer, Zamoscik, et al., 2013; Llera & Newman, 2010; Mantella et al., 2008; Thayer et al., 1996; Woody et al., 2014). Finally, more recent research replicated and extended these findings, perseverative thoughts having been associated with several adverse outcomes such as inflammation (Moons & Shields, 2015; for a review, see Szabo et al., 2022), impaired immunity (Brod et al., 2014; D'Acquisto, 2017; Reed & Raison, 2016), and worse physical health and chronic health conditions (Curhan et al., 2014; Leger et al., 2018; Seiler et al., 2020).

In summary, substantial empirical evidence, both experimental and correlational, supports the association between perseverative cognition and biological systems, including autonomic, endocrine, and cardiovascular functions. Perseverative cognition perpetuates stress activation by maintaining cognitive representations of events, thereby leading to long-term physiological consequences. This theory is therefore an 'allostatic load' model, which posits that the cumulative physiological activation induced by stress over time serves as the primary mechanism underlying the adverse somatic health effects of rumination (Brosschot et al., 2006). This stands in contrast to the 'reactivity' model, which emphasizes the significance of short-term physiological changes for health outcomes. Thus, it seems more accurate to focus on the cumulative physiological activation induced by stress over time, rather than the intensity of individual stressors or their immediate physiological changes, as the key driver of the deleterious effects of perseverative cognition on physiological health.

1.7 Summary and conclusion

Early theories characterized rumination as either a learned habitual thinking style, as suggested by the Response Styles Theory, or as a conscious process aimed at resolving goal discrepancies, as proposed by the Goal Progress Theory. The Habit-Goal framework reconciled these perspectives by suggesting that rumination initially arises due to goal discrepancies but evolves into a mental habit over time. By uniting these two perspectives, this framework effectively explains both state and trait rumination. Importantly, rumination has also been associated with impaired executive control in several theoretical models, including the Self-Regulatory Executive Function (S-REF) model, the impaired disengagement hypothesis, and the resource depletion account.

Recent advances have expanded upon these foundations to develop more comprehensive models accounting for multiple mechanisms underlying rumination. The HEXAGON model synthesizes the role of goal discrepancies, executive control, negative cognitive biases, abstract processing, and habit development. Meanwhile, the Perseverative Cognition Hypothesis elucidates how the repetitive nature of rumination prolongs physiological stress responses and contributes to long-term health consequences. Finally, the Repetitive Negative Thinking theory provides insights into the similarities between different types of repetitive thoughts, such as worry and rumination, while emphasizing their multifaceted nature and distinguishing between their process and content features.

In conclusion, this chapter offers a comprehensive review of various models and theories of rumination, emphasizing the multifaceted nature of this cognitive process. These models underscore the importance of understanding rumination as a dynamic (i.e., state rumination), repetitive, and often habitual pattern of thought, that can both be triggered and contribute to stress and negative affect. They also underscore the need to consider both trait and state aspects of rumination, as well as its specific features and their potential differential impacts. While the HEXAGON model integrates several of these theories and presents a comprehensive framework for understanding rumination, it also illuminates the need for further research into the precise ways in which these different mechanisms interact and contribute to rumination.

The subsequent chapters of this thesis will delve deeper into the research on rumination, with a particular focus on the role of executive control. This focus is predicated on the prominent role executive control plays in several of the models discussed, and its potential as a key mechanism in understanding rumination. Chapter 2 addresses the concept of executive control and reviews its associations with rumination, laying the foundation for the empirical investigations presented in the later sections of this thesis.

Chapter 2.

A narrative review of the associations between executive control and rumination

When I was a kid, my friends and I played the traditional child game ‘Red Light, Green Light.’ At the beginning of the game, we chose a target area and a leader. The rules are simple: when the leader has their back to the rest of the players, standing several meters away from the target area, the players can move towards the target. While the leader sings “Red light, green light, one two three”, everyone can move, but upon saying “Three”, everyone must stop moving. The leader turns around to face the players, and if the leader catches anyone moving, they either lose the game or must go back to the starting line. The rest of the game is simple: the goal is to go from A to B without being seen moving by the leader. I remember how, while the leader was counting, we ran as if our lives depended on it. But we had to be ready to, in an instant, go from running to freezing and standing still. The sequence then repeated until the remaining players arrived past the leader and earned bragging rights.

This game illustrates abilities that are important to humans in everyday life: holding rules in our minds, flexibly switching between rules and diverse types of actions, and withholding behavior and urges. At a minimum, failure to do so might cause slight nuisances or lousy performance on a task. Other related abilities might be, for example, to withhold an urge to say something we have not thought through, such as a vile comment uttered in response to a harsh feedback, or our ability to execute complex plans and unintuitive behaviors, such as when learning to dance or following a cooking recipe for the first time. The abilities involved in all those activities are typically referred to as executive functioning or executive control. Thanks to executive control, we can multitask, stay focused on a task despite distractions around us, execute complex actions from A to Z, inhibit behavior, and much more. In other words, executive control abilities allow us to execute and optimize behaviors depending on our goals.

The application of executive control is not limited to ‘exterior’ behaviors like abruptly stopping a run or resisting the urge to interrupt someone; it also helps regulate ‘internal’ behaviors, such as our thoughts. Rumination, characterized by its repetitive and habitual nature, serves as a prime example of this internal application of executive control. The theory posits that executive control is necessary to disengage from ruminative thinking and that impairments in executive control could exacerbate rumination (Koster et al., 2011). This hypothesis has spurred extensive research exploring the link between executive control and rumination. The aim of this chapter is to provide a narrative review of the evidence surrounding these associations, delving into how executive control intersects with and influences the process of rumination.

2.1 Executive control: definitions and conceptualizations

Researchers conceptualized executive control as high-level, complex processes that allow individuals to efficiently organize and regulate a series of cognitive processes (Baddeley, 1992) depending on the situation and their goals (Miller & Cohen, 2001). In the literature, various theories about top-down processes, so-called 'attentional' and 'executive' top-down processes, have been developed as these processes are crucial to our everyday life. Top-down attentional and executive processes are important for self-regulation (of thoughts and actions) and goal-directed behavior. They allow us to navigate through various activities: for instance, tasks that require decision-making, complex cognitive operations, conflict resolution, and overriding habitual responses (Allom et al., 2018).

Although researchers agree on what executive control broadly refers to, this research field has yet to agree on a universal definition and measurement forms (Baggetta & Alexander, 2016). Moreover, the field has yet to agree on a unique label to refer to executive functioning. Indeed, one can find many terms and definitions of executive functioning depending on their research field. For instance, these are some of the related terms and definitions one can find in the literature:

- **executive attention/attention control** as part of the attention network (Posner & Rothbart, 2007): "Executive attention involves mechanisms for monitoring and resolving conflict among thoughts, feelings, and responses" (Posner & Rothbart, 2007, p. 7);
- **attentional control**: "A general capacity to control attention in relation to positive as well as negative reactions" (Derryberry & Reed, 2002, p. 226);
- **attentional control** as used by Koster et al. (2011): "The ability to selectively attend to task-relevant information and to inhibit distraction by task-irrelevant information" (Koster et al., 2011, p. 139);
- **cognitive control**: "[…] The ability to override pre-potent responses and to inhibit the processing of irrelevant or previous relevant information. These abilities are related to the functioning of executive control processes, such as inhibition, switching, and updating in working memory (Miyake, Friedman, Emerson, Witzki, & Howerter, et al., 2000)" (De Lissnyder et al., 2012, p. 520);
- **executive attention/attention control: "**[…] The ability to control one's attention […]" (Engle, 2018, p. 190);
- **attention control:** "[..] The ability to focus on task-relevant information while resisting interference and distraction by task-irrelevant thoughts and events. […] also been referred to as executive attention, cognitive control, and more generally, executive functioning (Kane & Engle, 2002)." (Burgoyne et al., 2022, p. 3).
- and finally, **executive functions** are divided into updating, inhibition, and switching (Miyake & Friedman, 2012): this model will be described in the next section.

One group of researchers summarized the confusion regarding the conceptualization of executive functioning perfectly:

> "The earliest definition of executive functions described the construct as having 'four components' (Lezak, 1983, p. 507), with later descriptions defining executive functions as an 'umbrella term' (Chan et al., 2008, p. 201) for a family of 'poorly defined' (Burgess, 2004, p. 79), 'meta-cognitive' (Oosterlaan, Scheres, & Sergeant, 2005, p. 69), or 'cognitive control' (Friedman et al., 2007, p. 893) processes 'used in self-regulation' (Barkley, 2001, p. 5)." (Karr et al., 2018, p. 7).

The above is but a small illustration of the variety of terms and definitions, with ever so slight variations in meaning, of executive functioning. For the remainder of this thesis, we will mainly use the term 'executive control' to refer to the set of processes that aim to regulate information processing, attention (i.e., endogenous attention), and action in service of goal-directed behavior. To best present how executive control has been operationalized and measured, the next sections will describe two important models often used in the context of rumination: the unity/diversity framework (Miyake et al., 2000) and the attention network theory (Posner & Rothbart, 2007).

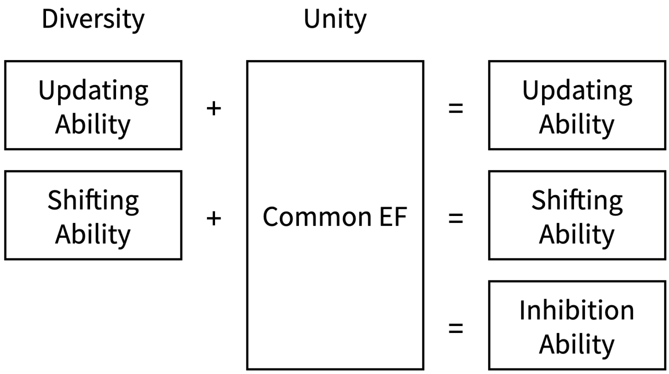
2.1.1 Unity/diversity framework of Executive Functions (EFs)

Although several attempts have been made to distinguish subcomponents of executive control, the 'unity/diversity' framework is one of the most researched frameworks to describe executive functions (Miyake et al., 2000). It focuses on three core executive functions: "updating (constant monitoring and rapid addition/deletion of working memory contents), shifting (switching flexibly between tasks or mental sets), and inhibition (deliberate overriding of dominant or prepotent responses)" (Miyake & Friedman, 2012, p. 9).

These executive functions show 'unity' and 'diversity.' They show unity as all executive functions correlate, reflecting that they all require similar underlying abilities. But they also show distinct associations with other variables, showing some separability, that is, diversity. The pattern of correlations between latent variable analysis of the three EFs illustrates this unity/diversity: they are all correlated, but not perfectly (i.e., 1.0). Other studies replicated this pattern, such as in research about intelligence (Burgoyne et al., 2022) and among youth (i.e., showing evidence for a unitary structure; Karr et al., 2018).

Friedman and Miyake later reparametrized their initial model composed of three executive functions (Friedman et al., 2008): instead of focusing on three executive functions, their new version of the unity/diversity framework highlights how each executive function can be decomposed into what is shared across all three executive functions (i.e., 'common executive function') and what is distinctive of each function (Figure 1). In doing so, they found no inhibition-specific factor—the variance of the inhibition-specific factor was wholly accounted for by the common EF factor (Friedman et al., 2008, 2011). Other research findings (e.g., Fleming et al., 2016; Ito et al., 2015) also hint at a common higher-order factor explaining the variance of the three executive functions (i.e., inhibition, updating, shifting; as initially conceptualized by Miyake et al., 2000).

Figure 1. Schematic representation of the unity and diversity of three executive functions



Note. The left side of this figure illustrates the latest version of the unity/diversity framework Miyake and Friedman have been developing. It illustrates that each EF is a combination of what is common to all three EFs (Common EF factor) and what is specific to each EF (Updating-Specific or Shifting-specific).

Mechanisms underlying the EF factors

Although the unity/diversity model is descriptive, Friedman and Miyake (2017) reviewed some proposed mechanisms (and their associated criticism) for the common EF, shifting-specific, and updating specific components. The following sections summarize this review.

Common EF factor mechanisms

The common EF factor comprises the variability explained by what researchers call 'inhibition'. Given that many tasks require some aspects of inhibition (e.g., avoiding being distracted, and suppressing prepotent responses), some researchers hypothesized that the common EF *is* inhibition (e.g., Valian, 2015). However, a first counterargument to this hypothesis is that this conceptualization of inhibition might be too broad as some researchers argue they group processes that can be distinguished empirically and conceptually (Friedman & Miyake, 2004; Hedden & Yoon, 2006; Nigg, 2000).

A second and alternative counterargument is that the idea of top-down 'inhibition' itself is unnecessary, even misleading, to explain what appears to be an inhibitory phenomenon (Hampshire & Sharp, 2015; Munakata et al., 2011). Instead, phenomena that result from top-down inhibition can be explained "With top-down activation of correct responses that compete with incorrect responses through local lateral inhibition" [1] (Friedman & Miyake, 2017, p. 194). This view forces us to reinterpret the role of frontal lobes implicated in inhibition: these frontal regions may be necessary for goal-related processes such as monitoring for goal-relevant information (Chatham et al., 2012; Hampshire et al., 2010). The observed inhibition of, for example, irrelevant stimuli or prepotent responses would emerge from the competition of several neural networks (Banich & Depue, 2015; Egner & Hirsch, 2005; Hampshire & Sharp, 2015; Munakata et al., 2011).

Altogether, Friedman & Miyake (2017) consider that the Common EF factor "reflects individual differences in the ability to maintain and manage goals, and use those goals to bias ongoing processing (Friedman et al., 2008; Gustavson et al., 2014; Miyake & Friedman, 2012)" (p. 194). This mechanism could explain why all EF tasks load on the Common EF factor, as all EF tasks require some form of maintaining an active representation of a goal. Moreover, inhibition tasks may only load on this factor precisely because they only require goal-maintenance (which allows avoiding strong prepotent responses and processing irrelevant information) and not Updating or Shifting abilities.

Shifting-specific factor mechanisms

Next, Friedman & Miyake's (2017) findings give insight into what abilities the Shifting-Specific factor might reflect. They found that the tasks involving switching often show opposite patterns of correlation to the tasks involved in Common EF. For example, the Common EF (r = .51) and Updating-Specific (r = .49) factors were positively correlated with intelligence at the phenotypic level, whereas the Shifting-Specific factor showed a negative correlation (r = -.24; Friedman et al., 2011). Task-switching paradigms loaded both on the common EF factor and the Switching-Specific factor, potentially reflecting that the tasks require selecting and maintaining active the correct tasks' instructions (i.e., Common EF abilities) and rapidly switching between instructions and goals (i.e., Switching-Specific abilities).

There might be an inherent trade-off between Common EF and Switching-Specific abilities (Herd et al., 2014). Some individuals might have difficulties replacing goal representations with new ones but have excellent performance on tasks requiring goal maintenance (i.e., a result of more active goal representations). Others might have weaker goal representations (i.e., have worse Common EF performance) and thus exhibit smaller switching costs which would not be suspected based on their worse performance on other tasks. This trade-off is referred to in the literature as the "stability/flexibility trade-off" (Herd et al., 2014).

Updating-Specific mechanisms

Finally, the Updating-Specific executive function refers to the ability to update specific information in working memory (Friedman & Miyake, 2017). It is distinct from the Switching-Specific factor because switching requires updating goals flexibly but only holding one goal at a

[1] Local lateral inhibition = "[…] the capacity of excited neurons to reduce the activity of their neighbors. Neurons that are firing inhibit the stimulation of surrounding neurons. Accordingly, only the neurons that are most stimulated and least inhibited respond." (R. A. Cohen, 2011, p. 1437)

time. In contrast, updating requires updating specific information held in working memory while maintaining other information simultaneously. Friedman and Miyake (2017) hypothesize that the variance explained by the Updating-Specific factor might be related to "the precision of the updating process, thought to be controlled by the basal ganglia (e.g., Frank et al., 2001)" (p. 195) and to mechanisms of memory, such as retrieval from episodic memory.

In summary, the unity/diversity framework decomposes executive functions into a common EF factor (what is shared across different executive functions tasks) and two specific components, shifting and updating (Miyake & Friedman, 2012). According to them, the common EF reflects the ability to actively maintain task goals and goal-related information which is required to bias lower-level processing. The shifting-specific component reflects flexibility, that is the ability to switch between task-set representations. Lastly, Friedman & Miyake (2017) hypothesized that the updating-component taps unto two mechanisms—effective gating of information and controlled retrieval from long-term memory. Importantly, as Friedman and Miyake (2017, p. 193) put it, the unity/diversity model is "primarily descriptive, quantifying how well-studied tasks cluster". Therefore, although links have been made between this psychometrics constructs and underlying neurological processes, this model should not be considered to be comprehensive nor a hypothesis about the neurological processes underlying executive control.

2.1.2 Attention Network Theory

Whereas the unity/diversity framework is prevalent in neuropsychological research, another conceptualization of executive processes is prevalent in psychopathology and cognitive neuroscience research: the Attention Network Theory (Posner & Rothbart, 2007). Attention Network Theory is a model of attention based on cognitive neuroscience research by Posner and colleagues (Petersen & Posner, 2012; Posner & Digirolamo, 1998). Rather than viewing attention as a unitary construct, it separates attention into three distinct components that rely on both specific and overlapping brain networks and voluntary and involuntary processes: the alerting, orienting, and executive control (also called attentional control) components (Fan et al., 2009; Petersen & Posner, 2012; Posner & Rothbart, 2007).

The alerting component refers to the ability to increase vigilance towards stimuli. The model distinguishes two types of alertness. Tonic alertness refers to wakefulness and arousal. In contrast, phasic alertness refers to (a) the ability to prepare one's attention, (b) increase one's readiness, and (c) attend to a stimulus based on external warning cues. In other words, "Alerting involves a change in the internal state in preparation for perceiving a stimulus" (Fan et al., 2009, p. 209). The orienting component refers to the ability to attend to and select information from many different sensory inputs. This process can be voluntary (endogenous), such as when a person deliberately orients their attention towards a stimulus, or reflexive (exogenous), as when a stimulus suddenly captures one's attention. The orienting process comprises three distinct components: (1) the ability to disengage attention from a stimulus, (2) move attention to a new target (in the same or a different modality), and then (3) engage attention with the new stimulus (Posner et al., 1984). Lastly, the executive control component, also referred to as attentional control, involves detecting and resolving conflicts between computations occurring in different brain regions to support goal-directed responses. More concretely, executive control will be instrumental in everyday life whenever there is a need for planning, making a decision, detecting errors, executing unintuitive responses, and overcoming habitual actions. Hence, executive control is also instrumental in our capacity to regulate positive and negative emotions.

As these three functions compose attention, they interact and coordinate depending on the attentional demands. A more active alerting component enhances orienting and response speed but inhibits executive control (Fan et al., 2009; Fuentes & Campoy, 2008). In contrast, efficient orienting can enhance executive control (Callejas et al., 2004, 2005) but inefficient orienting can inhibit executive control (conflict processing), such as when an invalid cue misleads attention in the wrong location (Fan et al., 2009). These results can be interpreted as evidence for the synergetic role of these attention components, working together towards shared goals. However, when task demands are high, these functions, due to their reliance on overlapping brain regions, will fight for a share of limited computational resources in these shared brain regions (i.e., anterior cingulate cortex, frontoparietal region).

2.1.3 Unity/Diversity framework and Attention Network Theory overlap

The unity/diversity framework of executive control aligns well with other executive functioning models, such as the one proposed by Posner and Petersen (Petersen & Posner, 2012; Posner & Petersen, 1989). Snyder et al. (2015) underscore the congruence between these models, noting their similarity in at least two key aspects.

First, both models share conceptual elements. The 'executive control' network of Posner & Peterson's model is defined similarly to the common EF factor of Friedman & Miyake: they support goal-directed behavior by providing top-down control that resolves conflicts between responses (Petersen & Posner, 2012). The sole difference is that, compared to Posner and Peterson's model of attention and executive control, Friedman & Miyake's unity/diversity framework of executive functions does not discuss the role of endogenous attention and how it interacts with the processes they study.

Second, the executive control network's empirical measurement is akin to the common EF's measurement, more precisely, inhibition. Indeed, the Attentional Networks Task (ANT; Fan et al., 2002), developed to measure the three networks, has a flanker inference component that allows assessing the executive control component of attention. Researchers often use flanker tasks to measure the inhibition executive function (Snyder et al., 2015): this task typically consists of a series of trials during which the participant is presented stimuli in the center of the screen; it can, for example, be a line of several arrows; at each trial, the participant must indicate the direction (e.g., left or right) of the central arrow; some trials are 'congruent', that is, the surrounding arrows point in the same direction as the central arrow; some trials are 'incongruent', that is, the surrounding arrows point in the opposite direction to the central arrow; and sometimes neutral trials can be included as well (i.e., no arrows surround the central arrow). The performance at flanker tasks strongly correlates with the inhibition of prepotent responses (Friedman & Miyake, 2004), which loads on a common EF factor (e.g., Friedman et al., 2008).

Moreover, executive control of attention has also been studied using the Stroop task, as explained by Posner & Rothbart (2007, p. 7): "Executive control of attention is often studied by tasks that involve conflict, such as various versions of the Stroop task. In the Stroop task, subjects must respond to the color of ink (e.g., red) while ignoring the color word name (e.g., blue) (Bush et al., 2000)." The Stroop task is one of the tasks involved in the battery of tasks used, for example, in Friedman & Miyake's (2017) latent factor analyses; similar to the flanker task, the Stroop task was considered a "prototypical Inhibition task" (Miyake et al., 2000, p. 57) and loaded on the common EF factor in the most recent version of the unity/diversity framework (Friedman & Miyake, 2017). In conclusion, executive control of attention and executive control through the lens of Miyake and Friedman's model are two ways of looking at the same coin; hence, their related research is complementary.

2.2 Bringing rumination and executive control together

These two conceptualizations of executive control, either through the unity/diversity framework of Friedman & Miyake (2017) or as a component of an attention network according to Petersen and Posner (2012), share one main commonality: they either partially or solely focus on clarifying the executive processes that make goal-dependent behavior and treatment of information possible. Discussing the nuances between the use of these terms and the models involved would cause us to lose the forest for the trees: all these models discuss overlapping processes that implicate the management of attention, working memory, and cognitive resources. Moreover, they all involve a component related to the ability to inhibit irrelevant information or discard no longer relevant information either from entering working memory (or occupying attention) or removing irrelevant information from working memory (or avoiding distractions). This process is of particular interest in better understanding rumination as several theories of the relation between executive control and rumination agree that rumination should be associated with more significant impairments in executive control or vice versa (Hertel, 2004; Koster et al., 2011; Linville, 1996; Whitmer & Gotlib, 2013).

Indeed, sometimes, one's goal might be to override habitual responses, especially if these habitual responses are maladaptive responses to distress. At other times, one might want to be able to let go of negative thoughts currently occupying their mind but might find themselves having trouble doing so. Hence, based on these observations, various researchers have hypothesized that deficits in top-down attention/executive processes could increase the tendency to ruminate in two main ways. First, deficits in top-down processes might induce difficulties in disengaging from (negatively valenced) thoughts, leading to the proliferation of negative content in working memory (Joormann, 2010; Joormann & Vanderlind, 2014; Koster et al., 2011). Second, deficits in top-down processes could impair one's ability to override habitual ruminative response tendencies when these habitual ruminative responses conflict with goal-directed behavior. Both hypotheses could explain how executive control deficits could increase the likelihood of developing repetitive internal thought patterns. Therefore, in the following sections, we will review the literature investigating the link between rumination and executive control deficits—more specifically, the ability to inhibit irrelevant information or discard no longer relevant information.

One model, the *impaired disengagement hypothesis*, attempts to explain how difficulties in disengaging from negative content (or, in other words, inhibiting the activation of negative information in working memory) are associated with rumination (Joormann et al., 2007). The impaired disengagement hypothesis postulates that difficulties in disengaging attention (i.e., performing executive/attentional control) in response to negative thoughts are likely to lead to prolonged rumination (Koster et al., 2011). Koster et al. (2011) define 'attentional control' in this context as "The ability to attend to task-relevant information selectively and to inhibit distraction by task-irrelevant information" (p. 139), which is sometimes reformulated into "The ability to direct attention towards or away from stimuli depending on current goals or task demands" (K. J. Hsu et al., 2015, p. 22). They further define and assimilate attentional control to executive functions as they use Miyake's et al. (2000) conceptualization of executive functions. Subsequent research citing this model also uses the term 'cognitive control' (e.g., De Lissnyder et al., 2012) to refer to what Koster et al. (2011) call attentional control. As explained previously, this thesis will mainly use the term executive control.

A perfect example of the interplay between executive control and rumination is depression. It has been shown that people suffering from depression have impaired executive control, which is associated with a higher tendency to ruminate, but mostly in severely depressed individuals (Joormann et al., 2007). Indeed, in healthy individuals, self-critical, negative thoughts are typically not congruent with their positive self-views. Hence, when faced with negative thoughts, people will experience cognitive conflict. Healthy individuals will disengage their attention from these negative thoughts (e.g., Mauss et al., 2007). As Koster et al. (2011) put it in their theoretical paper, "Successful disengagement of attention from negative thoughts then allows to reappraise the situation or distract from the situation altogether by focusing attention on other (task-relevant) stimuli or more positive distracters." (p. 140).

According to Koster et al. (2011), two types of impairment can disrupt this stage of conflict signaling and attention allocation: impaired conflict signaling or intact conflict signaling but impaired executive control. For instance, people with negative self-schemas (cf., Clark et al., 1999) will not perceive (or perceive less) cognitive conflict when they have negative thoughts (Foti & Hajcak, 2010) about themselves and consequently will not reallocate attentional resources. In other words, an absence of conflict signaling will result in sustained attention to negative self-referent information. This might be one reason depressive people often have more self-referential negative thoughts: because, as neurophysiological data shows, conflict monitoring worsens with an increasing number of depressive episodes (Vanderhasselt & De Raedt, 2009). In contrast, non-depressed participants tend to avoid negative information (De Raedt & Koster, 2010). If a person has intact conflict monitoring, however, sustained attention to self-referring negative information might be due to impaired executive control. Individuals with impaired executive control might have more difficulties discarding irrelevant thoughts and information, initially triggered by internal or external stressors that conflict with an individual's goals. Consequently, negative thoughts would proliferate and persist, leading to sustained rumination.

This hypothesis is in line with previous theories. For instance, Linville (1996) was one of the first to propose that deficits in inhibition may underlie rumination by facilitating the retrieval of irrelevant information and making it harder for ruminators to remove no longer relevant information from working memory. Similarly, Joorman (2010) postulated that depression is associated with inhibition deficits, leading to enhanced access of negative information to working memory and difficulties discarding negative information from working memory. This, in turn, contributes to ruminative thoughts. More recently, The H-EX-A-GO-N (Habit development, EXecutive control, Abstract processing, GOal discrepancies, Negative bias) model reiterated these hypotheses. It postulates that without efficient executive control, one might have more difficulties inhibiting or discarding irrelevant information; deficits in executive control may contribute to the maintenance of irrelevant thoughts in working memory and lower one's ability to override habitual responses (Watkins & Roberts, 2020).

An alternative hypothesis linking rumination with executive control is the dual-process model of cognitive vulnerability and resource depletion account (also discussed as the *resource allocation hypothesis* of rumination): it postulates that rumination occupies cognitive resources and requires deliberate effort to redirect attention (Hertel, 2004; Kofta & Sedek, 1998; Levens et al., 2009). These models postulate that rumination impairs effective resource allocation and leads to impaired executive control and difficulties on a wide range of EF tasks (Brinker, 2013; Philippot & Brutoux, 2008; Watkins & Brown, 2002). In other words, according to this view, rumination would deplete or occupy cognitive resources, which would interfere with concurrent executive processing, thereby impairing performance on concurrent tasks requiring EFs.

Previously mentioned research about the associations between rumination and executive control mainly pertains to depressive rumination (most often measured with the Ruminative Response Scale; Treynor et al., 2003). Yet, a related type of rumination, anger rumination, has also been associated with executive control. One theoretical model, the Multiple Systems Model (Denson, 2013), hypothesizes a bidirectional relation between anger rumination and executive control. According to this model, impaired executive control contributes to the onset of anger rumination after an anger-generating event; anger rumination, on the other hand, temporarily reduces executive control, which can facilitate aggressive behavior. Hence, this view helps to put into perspective the previously mentioned models. Indeed, it might not be the case that one causal direction between rumination and executive control is 'true' and the other is 'false'. As noted by the authors of the previously mentioned models (e.g., De Raedt & Koster, 2010; Denson, 2013; Hartlage et al., 1993; Hertel, 2004; Joormann et al., 2007) and as conceptualized in the Multiple Systems Model (Denson, 2013), there could be a bidirectional relationship between rumination and executive control.

Lastly, the Self-Regulatory Executive Function (S-REF) model (Matthews & Wells, 2004; Wells & Matthews, 1996) is at odds with all the previous models and hypotheses. In brief, according to this model, executive control's function is to monitor stimuli, implement strategies to reduce any discrepancy between a current state and a desired state, and monitor the implementation of the chosen strategy. Metacognitive beliefs bias (a) the appraisal of stimuli, (b) the choice of coping strategy, and (c) the monitoring of the implementation. From this perspective, metacognitive beliefs can lead a person to choose rumination as a preferred coping strategy and can reinforce the use of rumination even if it is ineffective at improving the situation (e.g., "If I think harder about it, I might be able to fix the situation or understand it better, and feel better"). Hence, this model is the only one that emphasizes the role of executive control in the implementation of coping strategies and illustrates how executive control is necessary to implement volitional rumination, with metacognitive beliefs potentially biasing the self-regulation enabled by executive control.

In summary, several theories link rumination to executive control. One set of theories (e.g., the impaired disengagement hypothesis) considers rumination a consequence of impaired executive control. In contrast, another set of theories considers that rumination can impair executive control. To shed light on the associations between rumination and executive control, I will review results from correlational studies (of self-reported rumination and behavioral measures of executive functioning), prospective studies, and experimental studies (i.e., studies investigating executive control training and neuromodulation stimulation). I will also discuss neurological underpinnings linking rumination to executive control. Finally, I will present a non-invasive neuromodulation technique that allows researchers to experimentally influence the cortical excitability of specific brain regions to study its impact on executive control or rumination.

2.3 Associations between rumination and poor top-down control

2.3.1 Cross-sectional research

Research has extensively demonstrated associations between impairments in executive control and a high tendency to ruminate (Beckwé et al., 2014; De Lissnyder et al., 2012). Correlational evidence supports associations between rumination and inhibitory control (De Lissnyder et al., 2010; Hoorelbeke, Koster, et al., 2016; Whitmer & Banich, 2007), working memory updating (Joormann et al., 2011; Joormann & Gotlib, 2008), and task-switching (Beckwé et al., 2014; De Lissnyder et al., 2010, 2012; Hoorelbeke, Koster, et al., 2016).

Three recent meta-analyses of studies using adult samples can help us better consider the number of published studies that investigated the relationship between rumination and executive control impairments. In a meta-analytic review of 34 studies, Yang et al. (2017) found that rumination was associated with impaired inhibition (21 studies, r = -0.23, p < .001) and set-shifting (11 studies, r = -0.19, p < .05), but not working memory updating (8 studies, r = -0.05, p = .47). However, the authors pointed out that the reason for the lack of association between rumination and working memory updating might be a lack of statistical power. Another meta-analysis of 70 studies by Valenas et al. (2017) found that rumination was not significantly associated with overall executive functioning (r = 0.09, p = 0.001). Interestingly, they also found small associations between rumination and shifting (24 studies, r = -0.17, p = 0.001) and rumination and inhibition (30 studies, r = -0.11, p = 0.012), but not with working memory (28 studies, r = 0.06, p = 0.12).

Zetsche et al. (2018) conducted a meta-analysis of 94 studies investigating the relationship between executive control (which they refer to as cognitive control) and rumination and worry. Before summarizing their results, a few important points need to be highlighted.

First, the authors relied on the unity/diversity framework, like the two previous meta-analyses, but further separated and distinguished a ‘discarding’ component from shifting, inhibition, and updating. The discarding component refers to the ability to discard no longer relevant information from working memory. This distinction further highlights the conceptual confusion of the executive control literature, as ‘discarding’ is considered an inhibitory process that helps to remove no longer relevant information from working memory, in contrast to another inhibitory process, ‘interference control’, which refers to the ability to control access to working memory (e.g., inhibiting irrelevant information from entering working memory). Moreover, in another paper, the authors themselves describe ‘updating’ as the ability to remove no longer relevant information from working memory (Zetsche et al., 2012). Hence, as the authors do not clearly explain their reasoning behind separating updating from discarding in their analyses, one can only hypothesize that the authors assumed that the typical updating tasks measure both interference control and discarding, whereas other more specific tasks were designed only to measure discarding. Second, another critical point is that it is not possible to directly compare the results of this meta-analysis with the two previously mentioned ones because Zetsche et al. (2018) controlled for depression in the effect sizes of the association between rumination/worry and executive control. Third, they do not provide separate effect sizes for each executive function component as they only compared effect sizes for discarding vs. all other executive functions taken together.

Putting these considerations aside, Zetsche et al. (2018) found that rumination and worry, taken together, had a small but significant overall negative association with executive control (170 effects sizes, r = –0.11, p < .0001) but that rumination had no correlation with executive control when controlling for depression (104 effect sizes, r = –0.04, p < .01). Repetitive Negative Thinking (RNT; i.e., rumination and worry taken together) and discarding were significantly associated (26 effects sizes, r = –0.2, p < .0001), and this association was significantly larger than the association with other executive control functions (144 effects sizes, r = 0.10, p < .01). Moreover, controlling for depression, rumination was significantly associated with discarding (16 effects sizes, r = –0.11, p = .005), but not with all other executive functions (88 effects sizes, r = 0.03, p = .06).

Similar results relating to the association between rumination and executive functions have been found in recent studies. For example, du Pont et al. (2019) investigated the associations between EF and rumination in a large sample of 764 individuals. Using latent variable analysis based on the unity/diversity framework (Friedman & Miyake, 2017), they found that rumination was weakly associated with the common EF factor (r = -0.11, p < 0.05) but not the Updating- and Shifting-Specific factors. Moreover, rumination and Common EF were uniquely related to internalizing (i.e., depression and general anxiety) and externalizing (i.e., antisocial personality and substance abuse) psychopathology. Although consistent with causal models of the association between rumination and executive control (e.g., the impaired disengagement hypothesis (Koster et al., 2011) or the resource depletion account (Levens et al., 2009)), the small association suggests that "potentially causal relations [between rumination and EFs] explain little variance in rumination/EFs, and may only partly contribute to psychopathology" (du Pont et al., 2019, p. 556).

In summary, the results from adult samples[2] support the hypothesis that rumination and impaired executive control are associated (see Table 1 for an overview). However, the overall association is small at best. And, despite the meta-analytical efforts, it is still unclear whether all core executive functions are impaired or only certain ones. Indeed, two meta-analyses found no relationship between working memory updating and rumination. In contrast, Zetsche et al. (2018) showed that rumination was specifically associated with difficulties discarding no longer relevant information from working memory, which is considered a part of updating content in working memory. Lastly, none of the meta-analyses found a moderating effect of the stimuli's emotional valence on the association between rumination and executive control. This is important to mention as it is a standing debate in the rumination literature: it has been hypothesized that because rumination carries emotional weight, it could be possible that executive control impairments are valence specific, but the meta-analyses mentioned do not support this hypothesis.

Several explanations could help make sense of these mixed results. Perhaps one reason that two meta-analyses failed to find associations between rumination and working memory is that many of the included effect sizes of the 'Updating' executive function refer to accuracy scores rather than reaction times. For instance, Yang et al. (2017) found eight effect sizes for updating-rumination: six of which used accuracy measures of updating tasks. Accuracy scores might be less sensitive than reaction times, leading to insufficient power to detect an association between updating and rumination. Hence, it is unclear to what extent the differences in associations of executive functions and rumination are due to the properties of the tasks (e.g., level of difficulty or how performance is assessed).

Additionally, past research does not help clarify whether rumination is associated with executive control in certain people but not all or whether rumination could be associated with better executive control in certain cases. Research has yet to answer the question, "among whom do we find an association between rumination and executive control, and what causes these

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[2] For readers interested in the associations between rumination and executive control in youth, I recommend the following two references:

- Mennies, R. J., Stewart, L. C., & Olino, T. M. (2021). The relationship between executive functioning and repetitive negative thinking in youth: A systematic review of the literature. Clinical Psychology Review, 88, 102050. https://doi.org/10.1016/j.cpr.2021.102050
- Snyder, H. R., Friedman, N. P., & Hankin, B. L. (2019). Transdiagnostic Mechanisms of Psychopathology in Youth: Executive Functions, Dependent Stress, and Rumination. Cognitive Therapy and Research. https://doi.org/10/gghnbz

differences?" Lastly, the results presented here, except for four out of the seventy studies included in Valenas et al. (2017), are based on cross-sectional data.

The issue with these meta-analyses and with correlational data is that it does not advance our understanding of the causal relationship between rumination and executive control. It is possible that the small associations found in these studies are mediated by a confounding variable. Therefore, the next sections focus on prospective and experimental research.

Table 1. Overview of cross-sectional research on the associations between rumination and executive control

Reference	Type of article	Executive control measure	Rumination measure	Association with rumination
Yang et al. (2017)	Meta-analysis of 34	Inhibition; Set-shifting; Working memory updating	Trait rumination	Association between rumination and impaired inhibition and set-shifting, but not working memory updating
Valenas et al. (2017)	Meta-analysis of 70 studies	Overall executive functioning; Shifting; Inhibition; Working memory (updating)	Trait rumination	No significant association with overall executive functioning, small associations with shifting and inhibition, but not working memory
Zetsche et al. (2018)	Meta-analysis of 94 studies	'Discarding' component; All other executive functions taken together	Trait rumination and trait worry	Rumination and worry, taken together, were associated with difficulties discarding no longer relevant information from working memory. The association with other executive control functions was smaller. Stimuli valence and type of RNT were not significant moderators. Rumination was only associated with discarding, not with the other executive control functions.
du Pont et al. (2019)	Large study with a sample of 764 young adults	Common executive functioning factor; Updating- and Shifting-Specific factors	Trait rumination	Rumination was weakly associated with the common executive functioning factor, but not the Updating- and Shifting-Specific factors

2.3.2 Prospective studies

While theories linking rumination to impaired executive functioning suggest a causal relationship, only a limited number of studies have empirically examined the directionality of this causation. Several studies have investigated whether impaired executive control contributes to increased rumination in prospective studies with the idea that either baseline executive control/rumination or changes in executive control/rumination over time will inform about their causal relationship. Although prospective designs are limited in their ability to conclusively establish causality, they are instrumental in investigating the potential causal pathways.

For instance, in a five-year longitudinal study, Ronold et al. (2020) examined the relationship between executive functions, depression, and rumination, in a sample of individuals suffering from a first episode of major depressive disorder matched to a control group. There was no significant association between the performance on an executive functioning task measuring inhibition and switching (The Color Word Interference Test (CWIT); Delis et al., 2012) at T1 and rumination at T3 (5 years later). In another study with 37 undergraduates, higher switch costs for emotional information (angry faces) at baseline moderated the association between stressful life events and higher brooding rumination (effect size r = .44, p = .003) measured six weeks later (De Lissnyder et al., 2012). Another prospective study of 111 undergraduates found impaired inhibition of negative material predicted rumination six months later, controlling for baseline rumination and depression (Zetsche & Joormann, 2011). In another prospective study of thirty remitted depressive adults, worse switching performance (i.e., switching away from and to emotional information) predicted a higher tendency to ruminate one year later (Demeyer et al., 2012). Moreover, rumination fully mediated the relationship between baseline impaired switching performance at baseline and depression (T2, one year later). Interestingly, cross-sectional correlations between rumination and switching performance were non-significant.

Some studies investigated how executive control is associated with **state rumination**. Ng et al. (2022) measured executive control (using a latent factor based on a battery of tasks) at one time point and daily rumination for eight days in a sample of 782 middle-aged and older American adults—which is considerably higher than samples included in the previously mentioned studies (e.g., N = 37, De Lissnyder et al., 2012; N = 111, Zetsche & Joormann, 2011). Lower baseline executive control was associated with higher daily rumination on day one and steady levels of (higher) rumination over time. Moreover, the association between executive control and rumination did not differ between middle-aged and older adults.

Some studies also investigated the association between executive control and rumination using executive control self-report measures. Importantly, whereas executive control tasks measure the performance of a person at a specific time, trait questionnaires of manifestations of executive control in everyday life measure self-reported executive control abilities in general or over a specific period. For instance, a prospective study (two time points) by Mills et al. (2016) showed that self-reported attention control mediated the relationship between various forms of repetitive negative thinking and symptoms of psychopathology (the two measurements were separated by 4.5 weeks on average). Another prospective study (three time points, separated by three months each) showed that self-reported attention control mediated the relationship between sleep disturbance and repetitive negative thinking (Cox et al., 2018). Finally, Letkiewicz et al. (2014) found that worse self-reported attention control was significantly associated with increased rumination three months later (shifting, $r = 0.49$; inhibition, $r = 0.45$; working memory, $r = 0.52$).

In contrast, fewer studies investigated the inverse causality, that is, rumination predicting worse executive control (i.e., the resource depletion account). One prospective study among adolescents found that baseline rumination predicted worse switching performance 15 months later but not sustained attention, divided attention, or working memory capacity (Connolly et al., 2014). In the opposite direction of causality, T1 executive control predicting T2 rumination was not significant.

In conclusion, longitudinal evidence lends support to the direction of causality between executive control and rumination postulated by the impaired disengagement hypothesis (Koster et al., 2011) and the HEXAGON model (Watkins & Roberts, 2020)—that impaired executive control leads to an increased tendency to ruminate (see Table 2 for an overview). However, there was a lack of studies investigating the alternative hypothesis: only one study found support for the resource depletion account (Connolly et al., 2014). Moreover, there was high heterogeneity in addition to the low number of studies: many different time scales were used in these prospective studies, spanning from 8 days to 5 years; some studies used non-clinical samples, whereas others used clinical samples; and the tasks used to measure executive control varied greatly. Lastly, only one study investigated the association between impaired executive functioning and *state* (daily) rumination. Overall, temporal evidence regarding the direction of causality between rumination and executive control is weak and based on a small number of heterogeneous studies.

Table 2. Overview of prospective studies on the associations between rumination and executive control

Reference	Time span & number of measurements	Sample characteristics	Executive control measure	Rumination measure	Main findings
Ronold et al. (2020)	5 years – 3 measurements	23 with first episode of major depressive disorder and 20 matched controls	Color Word Interference Test (CWIT)	RRS/RRQ	No significant association between EC at T1 and rumination at T3
De Lissnyder et al. (2012)	6 weeks – 2 measurements	37 undergraduates	Switch costs for emotional information	RRS: Brooding subscale	Worse EC (higher switch costs) predicted higher brooding rumination
Zetsche & Joormann (2011)	6 months – 2 measurements	111 undergraduates	Inhibition of negative material	RRS	Worse EC (Impaired inhibition of negative material) predicted rumination six months later
Demeyer et al. (2012)	1 year – 2 measurements not specified	30 remitted depressive adults	Switching performance	RRS	Worse EC (worse switching performance) predicted a higher tendency to ruminate one year later.

Reference	Time span & number of measurements	Sample characteristics	Executive control measure	Rumination measure	Main findings
Mills et al. (2016)	4.5 weeks (2 measurements)	376 undergraduates	Self-reported attention control (ACS)	Various forms of repetitive negative thinking (RRS for rumination)	Self-reported trait EC (T1) mediated the relationship between repetitive negative thinking (T1) and symptoms of psychopathology (T2).
Cox et al. (2018)	9 months (3 time points, separated by 3 months each)	445 undergraduates	Self-reported attention control (ACS)	Repetitive negative thinking	Self-reported EC mediates the relationship between sleep disturbance and repetitive negative thinking
Letkiewicz et al. (2014)	3 months (measurements not specified)	52 undergraduates	Self-reported executive functioning (BRIEF)	RRQ	Worse self-reported EC was significantly associated with increased rumination three months later
Ng et al. (2022)	8 days Daily measurements for 8 days	782 middle-aged and older American adults	Latent factor EC based on a battery of tasks	Six items measuring daily rumination	Lower baseline EC was associated with higher daily rumination on day one and steady levels of rumination over time
Connolly et al. (2014)	15 months (measurements not specified)	200 adolescents	Switching performance; Sustained attention; Divided attention; Working memory capacity	CRSQ	Baseline rumination predicted worse switching performance 15 months later but not sustained attention, divided attention, or working memory capacity Note that this is the only prospective study that provides some evidence for the resource depletion account

Note. EC: Executive control; RRS: Ruminative Response Scale; RRQ: Rumination-Reflection Questionnaire (RRQ); ACS: Attentional Control Scale; BRIEF: Behavior Rating Inventory of Executive Function; CRSQ: Children's Response Styles Questionnaire.

2.3.3 Experimental research

Experimentally studying the association between rumination and executive control is the most direct way to study their causal relationship. We can distinguish (a) attempts at manipulating (state) rumination and studying the effect of this manipulation on executive control and (b) attempts at manipulating executive control (either temporarily or through long-lasting changes) and studying the effect of this manipulation on the susceptibility to ruminate in response to a trigger (state rumination) or the tendency to ruminate (trait rumination).

Increased rumination impairs executive control

Only a handful of studies investigated the impact of rumination on executive control by experimentally manipulating rumination (see for an overview). For instance, inducing rumination in depressive participants reduced their executive control performance (Watkins & Brown, 2002). However, the main limitation is that this study used a random sequence generation task to measure executive control: it only uses a generic performance score, and it is unclear which facet of executive control is measured (N. Towse & Valentine, 1997). Another study investigated the effect of a rumination induction on the performance on a Stroop task in dysphoric versus non-dysphoric college students (Philippot & Brutoux, 2008). Philippot and Brutoux (2008) replicated the association between rumination and impaired executive control found by Watkins and Brown (2002): a rumination induction was associated with worse inhibitory performance on the Stroop task among dysphoric students but not non-dysphoric students. Moreover, they found a non-significant effect of rumination on switching performance, indicating that rumination does not influence all executive functioning processes equally. Whitmer and Gotlib (2012) found the opposite results: depressed participants induced to ruminate had worse switching performance compared to a control group, but their inhibition was not affected by rumination. Curci et al. (2013) found that inducing negative mood increased state rumination which in turn reduced working memory capacity in line with the resource depletion account. Moreover, in a study by Hertel (1998) eliminating the possibility for dysphoric participants to ruminate by inducing a distraction eliminated the impairments on a controlled retrieval paradigm, with dysphoric participants performing similarly to non-dysphoric participants only in the distraction induction condition, but not in the rumination induction or the resting period condition. This means that ruminating is responsible for worse executive control performance. Lastly, in a sample of fifty-nine students, induced *self-absorbed rumination* was associated with more difficulties in shifting compared to distraction but not with inhibition or updating (Ding et al., 2015). Interestingly, induced *self-distanced rumination* (i.e., taking a self-distanced perspective when processing thoughts) was associated with worse inhibition, but not worse shifting or updating, compared to distraction.

However, some studies were unable to replicate the causal impact of state rumination on executive control. Roberts (2013) investigated the association between state rumination and cognitive inhibition in a series of five studies in her thesis[3]. In two studies, inducing rumination among dysphoric and non-dysphoric individuals had no impact on executive control (i.e., as measured by the performance on a modified Sternberg task (Joormann & Gotlib, 2008)). In these two studies, Roberts used Nolen-Hoeksema and Morrow's (1993) rumination and distraction tasks. In the rumination condition, participants are asked to focus on items that are self-focused, emotion-focused, and symptom-focused. The limitation of this method is that it lacks a state measure of rumination to confirm that the manipulation was successful. Therefore, in three

[3] Except for the third study of that thesis, all the other studies are unpublished.

more studies, Roberts (2013) induced rumination by cueing personal unresolved goals and used a measure of state rumination as a manipulation check. The three additional studies using this method of induction — one of which has been published (Roberts et al., 2013) — found no impact of state rumination on either resolving interference from irrelevant emotional material or inhibiting prepotent responses.

How rumination is induced in participants might influence the results in two ways. First, as Ding et al. (2015) suggested, the type of rumination induced could cause some inconsistencies found across these studies in the way they induce different types of rumination. They discovered that self-focused rumination impairs switching ability, while self-distanced rumination affects inhibition. They proposed that self-distanced rumination could be more cognitively taxing, leading to a depletion of executive control resources, a concept known as the ego depletion effect (Baumeister et al., 2018; Dang, 2018; Forestier et al., 2021; Vohs et al., 2021). In contrast, self-immersed rumination could prevent participants from transitioning away from ruminative thinking, thus hindering their performance when required to shift between mental sets (Ding et al., 2015). Second, rumination induction might not induce *enough* ruminative thoughts to test the resource depletion account. Except for Roberts' (2013) studies, no study included a measure of state rumination as a manipulation check. And in Roberts' (2013) studies, participants reported on average a relatively low number of ruminative thoughts, with some participants having no ruminative thoughts—even though the rumination induction led to statistically significant changes in ruminative thoughts.

To conclude, the impact of induced state rumination on executive functioning remains uncertain due to the heterogeneity of the available evidence. The effect seems to fluctuate based on several variables, such as the population type (for instance, depressed, dysphoric, or control participants), the specific executive function being assessed (like switching, inhibition, or updating), the tasks employed for measurement, and how rumination is induced. Unlike six other published studies, Roberts' (2013) series of five studies (only one of which was published) found no support for the resource depletion account. This raises doubts about publication bias favoring significant results. Roberts' results also suggest the rumination inductions may not have elicited enough ruminative thoughts to impact executive functioning. Thus, the varied results regarding the influence of state rumination's effect on executive control neither firmly support nor refute the resource depletion account.

Table 3. Overview of studies investigating the impact of rumination induction on executive control

Reference	Manipulation	Cognitive task	Manipulation check	Main Findings
Watkins & Brown (2002)	Rumination induction vs. distraction	Random Sequence Generation (inhibition)	State rumination and mood measures	Compared to a distraction condition, inducing rumination in depressive participants reduced their performance on the task, reflecting poorer inhibition according to the authors. Non-depressed participants were unaffected by the rumination induction.

Reference	Manipulation	Cognitive task	Manipulation check	Main Findings
Philippot & Brutoux (2008)	Rumination induction vs. distraction	Stroop Task (inhibition and switching)	None	Dysphoric students but not non-dysphoric students had worse inhibitory performance on the Stroop task in the rumination condition compared to the distraction condition. There was no significant effect of the rumination condition on switching performance.
Whitmer & Gotlib (2012)	Rumination induction vs. distraction	Backward inhibition task (inhibition and switching)	State affect measure	Depressed participants induced to ruminate had worse switching performance compared to the distraction condition, but their inhibition was not affected by rumination. In contrast, rumination induction did not affect healthy participants.
Curci et al. (2013)	Negative mood induction vs. neutral condition	Ospan (Working Memory Capacity)	Self-reported emotions scale	Inducing negative mood increased state rumination which in turn reduced working memory capacity.
Hertel (1998)	7-min break consisting of: Self-focused (rumination) vs. distraction vs. unconstrained condition	Controlled Retrieval Paradigm (controlled retrieval)	None	Eliminating the possibility for dysphoric participants to ruminate by inducing a distraction eliminated the impairments on a controlled retrieval paradigm: that is, participants remembered more of the pairs they were presented before the 7-min break.
Ding et al. (2015)	Self-absorbed rumination vs. self-distanced rumination induction vs. distraction	Local-global task (shifting), stop signal task (inhibition), keep track task (updating)	Self-reported manipulation check and judges evaluating what participants had written during the rumination induction	Self-focused rumination impairs shifting ability, while self-distanced rumination affects inhibition, compared to a distraction condition.
Roberts (2013) – study 1	Rumination induction vs. distraction	Modified Sternberg Task (inhibition: resistance to proactive interference)	State mood and state self-focus measures	No effect of the rumination induction on the performance on the task. The effect of the rumination induction did not last through the cognitive task. Hence, it seems the task distracted participants from ruminating, which could explain the null finding.

Reference	Manipulation	Cognitive task	Manipulation check	Main Findings
Roberts (2013) – study 2	Rumination induction vs. distraction	Modified Sternberg Task (with encouragements to maintain their focus on the thought content and style elicited by the inductions) (inhibition: resistance to proactive interference)	State mood and state self-focus measures	The effect of the rumination induction was effective but only for dysphoric participants. However, induced rumination did not impair performance on the cognitive task.
Roberts (2013) – study 3, published as Roberts et al. (2013)	Goal-cueing manipulation (resolved vs. unresolved goal)	Modified SART (inhibition: prepotent response inhibition)	State rumination, mood, and self-focus measures during the task	Trait rumination moderated the impact of the goal manipulation on state rumination (i.e., participants high in trait rumination had higher state rumination following the unresolved goals manipulation). In the rumination condition, participants adopted a more conservative style of responding: they were slower and more accurate on the SART.
Roberts (2013) – study 4	Goal-cueing manipulation	Modified SART (constrained, addressing the speed/accuracy trade-off) (inhibition: prepotent response inhibition)	State rumination, mood, and self-focus measures during the task	Trait rumination moderated the impact of the goal manipulation on state rumination (i.e., participants high in trait rumination had higher state rumination following the unresolved goals manipulation). Inducing state rumination did not cause performance deficits; there were no differences in error rates but, in the unresolved goals condition (i.e., the rumination condition), participants responded faster compared to the resolved goal condition.
Roberts (2013) – study 5	Goal-cueing manipulation	Modified Sternberg Task (inhibition: resistance to proactive interference)	State rumination, mood, and self-focus measures during the task	No effect of rumination induction on the performance of the modified Sternberg task.

Note. Modified Sternberg Task see Oberauer (2005); SART = Sustained Attention to Response Task (SART; the frequency of errors of commission in the SART is considered a measure of prepotent response inhibition, with lower errors indicating better response inhibition; Robertson et al., 1997).

Improvements in executive control reduce rumination

Whereas the previous section reviewed experimental studies that tested the resource depletion account, this section reviews experimental studies directly investigating the impaired disengagement hypothesis by improving executive control. One way to improve executive control is by training it. It assumes that executive control is malleable and that, as with many other skills, repeated practice can improve one's executive control abilities. Such executive control training is called 'cognitive control training' (CCT). Although some authors debated its effectiveness (Shipstead et al., 2012), researchers investigated whether improving executive control through training can reduce rumination.

Executive control training using the Paced Auditory Serial Addition Task (PASAT)

Several studies used a specific type of executive control training: an adaptive version of the Paced Auditory Serial Addition Task (PASAT). Some authors theorize that this task creates frustration, potentially triggering rumination. Such training thereby involves practicing executive control to refocus on the task rather than ruminate (Siegle et al., 2007, 2014). Results indicate that six sessions of executive control training using the PASAT reduced trait rumination in depressed individuals compared to treatment as usual (Siegle et al., 2014). Similarly, ten training sessions reduced trait depressive rumination in major depressed patients (Vanderhasselt et al., 2015). This effect was replicated in undergraduates using ten executive control training sessions with the PASAT: the training reduced trait rumination four weeks after the training and reduced participants' reactivity after stress induction in the lab (Hoorelbeke et al., 2015).

A handful of studies investigated the impact of internet-delivered executive control training. PASAT training delivered over the internet reduced rumination in patients with remitted depression immediately after two weeks of 10 training sessions and at three months follow-up (Hoorelbeke & Koster, 2017). However, Vervaeke et al. (2021) did not replicate these effects as the PASAT training did not reduce rumination in a sample of patients with remitted depression (considering three months and six months follow-ups). Lastly, in a recent study, participants had decreased repetitive negative thinking (i.e., an umbrella term for rumination, worry, and related phenomena) in a varied sample with elevated repetitive thinking following gamified and internet-delivered adaptive PASAT training (Hoorelbeke, Vervaeke, et al., 2022). However, even though this reduction in RNT is in line with expectations and in line with previous results, the reduction in RNT cannot be attributed specifically to the executive control training as there was no control condition.

Two studies investigated the effect of executive control training using repeated assessments in daily life. In an unselected student sample examined via assessments in daily life (eight assessments a day for seven days), ten PASAT training sessions reduced only state rumination in response to low levels of positive affect but not rumination in response to negative affect (Hoorelbeke, Koster, et al., 2016). More recently, Hoorelbeke et al. (2022) examined the effects of PASAT training using an intensive longitudinal design, during which remitted depressed patients answered questions six times a day for four weeks after initial baseline measurements. The first week served as a baseline assessment of daily functioning; during weeks two and three, participants completed the online training procedure (ten sessions); the fourth week allowed to evaluate the impact of the training procedure on daily functioning. Compared to the active control condition, the training condition showed a more substantial decrease in rumination over time, specifically when participants' affect was two SD above their mean. In contrast, the use of rumination remained stable over time in situations when participants had negative affect (two SD below their mean). These two studies taken together could indicate that executive control training does not reduce the use of rumination as an emotion regulation strategy in the face of stress or negative affect, but instead allows participants to better control their (habitual) emotion regulation strategies in the absence of direct stressors. These results could also mean that improving executive control may facilitate the use of maladaptive emotion regulation strategies such as rumination by helping people better engage in such strategies.

Despite these encouraging findings, two recent studies failed to find similar training effects. For instance, six sessions of PASAT training reduced depressive symptomatology but not rumination in a sample of 72 university students (Lass et al., 2021). Moreover, a randomized, double-blind, placebo-controlled pre-registered trial with major depressive disorder patients did not find an adjunctive effect of PASAT training on rumination or depression compared to an active control group (i.e., a task that did not require executive processes, Ferrari et al., 2021). Similarly, another article investigated the long-term effects of the PASAT training (i.e., same participants as Hoorelbeke et al. (2022), discussed in the previous paragraph). In this article, they show that executive control training did not reduce rumination at one-year follow-up, as both groups (active control and training conditions) had experienced a similar significant reduction in rumination (Hoorelbeke et al., 2021).

The research on PASAT training has been recently reviewed in a meta-analysis of nineteen studies (Zwalmen et al., 2023). They found a small significant effect of training on rumination immediately after the training, but not at follow-up. This lack of effect at follow-up might be due to fewer studies including a follow-up measurement, and therefore lower statistical power, or too small samples sizes in the included studies, and therefore lower statistical power to find a small effect. Interestingly, the effect of training on rumination was higher in non-healthy populations for post-training rumination. Finally, the number of sessions of training was not a significant moderator of these effects; it is, therefore, still unclear whether more training sessions improves the effect of cognitive training on rumination. In summary, PASAT training seems to have some beneficial impacts on rumination, but more research is needed to examine the long-term benefits.

Other types of executive control training

Studies using other types of training obtained mixed effects as well. Using an adapted negative priming task, five training sessions over three weeks reduced state rumination post-training and at a two-week follow-up following the recall of a negative personal event (Daches et al., 2019). However, the training did not reduce trait rumination. Two other studies that used a dual n-back training found no effect of the training on trait rumination. First, two separate experiments indicated that a six day training with a dual n-back task improved performance on the trained task compared to a control group but the training had no effect on trait rumination and depression measures (post-training and at two-weeks follow-up), nor did the effect transfer to other executive control tasks (Onraedt & Koster, 2014). In a double-blind randomized control trial, patients with depression and/or anxiety underwent an executive control training consisting of training six times a week for four weeks. The training resulted in improved performance on the trained tasks, with limited transfer to other tasks, but did not reduce trait rumination compared to the control group (Wanmaker et al., 2015). Finally, in a study that used an inhibition task (negative affective priming task) for executive control training (Daches & Mor, 2014), participants did four training sessions during a two-week period, separated in three conditions, a control condition, a negative training condition (i.e., trained to evaluate negative words and to regard as irrelevant the neutral words) and an irrelevant training condition (i.e., trained to regard negative stimuli as irrelevant and evaluate neutral words). The negative condition led to worse inhibition of negative words and the irrelevant condition led to increased inhibition of negative words, although this effect was not significant. There was a significant albeit small decrease in trait rumination scores (i.e., brooding specifically) in the irrelevant condition. However, these changes in brooding were not significantly correlated with the changes in inhibition scores. These results therefore do not support that improving inhibition leads to reduced rumination.

In contrast, two intensive longitudinal studies in daily life found some evidence the effectiveness of executive control training at reducing rumination. First, 21 days of mobile-based training using an adapted dual n-back task reduced trait rumination in anxious individuals at one-month follow-up (Pan et al., 2020). This study distinguishes itself from all the previous studies by (1) its training length (21 days), (2) the distinction between emotional executive control training versus non-emotional executive control training versus a control group, (3) the pre- and post-testing of a battery of executive control tasks to verify for transfer effects, and (4) the inclusion of EEG measurements. Pan et al. (2020) found that emotional executive control training had a more pronounced effect than non-emotional executive control training on rumination (emotional $d = 0.69$ vs. non-emotional $d = 0.45$). Moreover, the training effect was associated with an improvement in a neural index of rumination as measured by the EEG (see Pan et al., 2020, for more details). Second, another recent study sought to test an executive control training paradigm based on a newly developed working memory updating task (Roberts et al., 2021). The training consisted of twenty online training sessions and participants were allocated to one of three groups: non-adaptive training (control group), neutral adaptive training (an active group with neutral stimuli), and emotional adaptive training (an active group with negative emotional stimuli). Adaptive training using neutral stimuli, but not adaptive training with negative stimuli, significantly decreased state rumination (in response to a stressor) post-training compared to non-adaptive training.

Single session training

Evidence from single training session studies is mixed. A single session of executive control training using a flanker task reduced state rumination compared to a control condition (Cohen et al., 2015). Yet, in a study on healthy participants, executive control training (using a dual n-back task) did not improve state rumination after a rest period, regardless of whether or not it was combined with neuromodulation (De Putter et al., 2015). In one study, trait rumination moderated the effect of a single session of executive control training (adaptive n-back task) on stress response: only participants that were high in trait rumination had a reduction in salivary cortisol (Quinn et al., 2014). Although it does not provide direct evidence of the effect of training on rumination (as rumination was not an outcome in this study), this result indicates that people high in trait rumination can benefit more from executive control training, perhaps because of impaired executive control. Finally, in a study with students, a single training session was ineffective at reducing state rumination (Daches et al., 2015).

Neurofeedback training

Lastly, one original way to improve executive control and reduce rumination could be neurofeedback paradigms. Indeed, EEG neurofeedback can activate the prefrontal cortex and improve executive functions (Enriquez-Geppert et al., 2013). It consists of computerized tasks linked to EEG inputs which translate activity in specific brain regions in real-time through sounds or visual feedback. In this way, participants can learn to regulate their EEG activity.

Yu et al. (2020) investigated the effect of a neurofeedback training paradigm (20 sessions, 2-3 times per week) to enhance executive functions on rumination and depression. Participants learned to regulate the peak alpha frequency (PAF), which is an index of an individual's level of cognitive preparedness (Angelakis, Lubar, & Stathopoulou, 2004; Angelakis, Lubar, Stathopoulou, et al., 2004; Bazanova & Vernon, 2014) and has been linked to executive functioning. Such neurofeedback of the PAF has been effective in improving cognitive processing speed and executive function (Angelakis et al., 2007). In a sample of twenty-six students with high depressive symptomatology and high rumination, Yu et al. (2020) found that PAF neurofeedback training, versus sham training, enhanced executive control (i.e., updating) and reduced rumination and depression. Hence, neurofeedback seems to be a promising tool to improve rumination and executive control, but further research is needed.

Summary of executive control training research

Overall, the cumulative evidence of the efficacy of executive control training indicates that it can reduce rumination (state or trait), which is in line with the hypothesis that executive control plays a causal role in rumination (see Table 4 for an overview). Most studies used an adaptive PASAT task in their training conditions, but there is also encouraging evidence supporting the use of dual N-back tasks. As an alternative to augment executive functions, neurofeedback seems promising, although only one study investigated this type of training (Yu et al., 2020).

However, there are limitations. First, all studies either used a no-training control group or an active-training control group. No-training control groups might overestimate the effect of training, whereas active control groups might not adequately control for placebo effects as participants' expectations are not matched between treatment and control groups (Boot et al., 2013; see Gobet & Sala, 2022 for a recent discussion and some cautionary notes on what should be considered as active control groups). Second, it is possible that some studies did not find an effect of executive control training as the training did not improve executive functioning in the first place. Instead, increased performance on the task reflects a task-specific learning effect but not an improvement in executive functioning (e.g., Hofmann & Förster, 2019); this assumption is supported by the fact that some studies did not find transfer effects to an untrained task. Alternatively, some studies did not evaluate transfer effects to an untrained executive task, which leaves the results regarding cognitive mechanisms of the effect of training on rumination open for interpretation (there are some exceptions, however: Pan et al., 2020; Roberts et al., 2021). Other important factors could be the timing of measurements (e.g., one-year follow-up vs. three months; Ferrari et al., 2021; Koster et al., 2017) and baseline performance: on the one hand, worse baseline executive performance might give more room for the training to effectively improve executive skills, but, on the other hand, worse baseline performance might be associated with difficulties in engaging with the training and thus fewer benefits from the training (De Raedt, Vanderhasselt, et al., 2015; Moshier & Otto, 2017; Siegle et al., 2014). Moreover, it is unclear how training affects state *vs.* trait rumination; most studies only investigated the effect of training on state or trait rumination. Finally, using emotional material for the training might have additional benefits (Pan et al., 2020), but this benefit might depend on the type of executive functions trained (Roberts et al., 2021).

In summary, the mixed findings of executive control training on rumination support a causal role of executive functions in rumination. Yet, the causal link is not always found nor is the direction of causality clear, as improving executive control may help people ruminate better (Hoorelbeke, Van den Bergh, et al., 2022). These mixed findings also warrant further research to address the current limitations (i.e., see whether the results hold once all limitations have been accounted for) and investigate potential moderators of the effect and efficacy of executive control training for rumination[4].

Table 4. Overview of executive control training studies and their effect on rumination

Reference	Type of training	Number of sessions and time span	Transfer on other tasks	Rumination outcome measure(s)	Main findings
Siegle et al. (2014)	PASAT	6 sessions over two weeks	Not measured	Trait rumination in depressed patients	EC training reduced trait rumination
Vanderhasselt et al. (2015)	PASAT	10 sessions (5/week for two weeks)	Not measured	Trait rumination in major depressed patients	EC training reduced trait depressive rumination and reductions in rumination were associated with improvements in working memory during training

[4] For a broader discussion of the executive control/cognitive control training research field, I redirect the reader to the excellent and nuanced review of Gobet and Sala (2022), "Cognitive Training: A Field in Search of a Phenomenon".

Reference	Type of training	Number of sessions and time span	Transfer on other tasks	Rumination outcome measure(s)	Main findings
Hoorelbeke et al. (2015)	PASAT	10 sessions over two weeks	No transfer effect	Trait and state rumination in undergraduates	Improvements in task performance were associated with reduced trait rumination in the EC training group but not in the active control group immediately after the training. Participants in the EC training group had also reduced trait rumination in response to a naturalistic stressor, at four-week follow-up. State rumination following a stressor was not clearly affected by condition.
Hoorelbeke & Koster (2017)	PASAT	10 sessions over two weeks	Yes (post-training and at follow-up)	Rumination in patients with remitted depression	EC training reduced trait rumination post-training and at 3-months follow-up compared to an active control condition
Vervaeke et al. (2021)	PASAT	10 sessions over two weeks	Yes	Trait rumination in patients with remitted depression	No effect of EC training on trait rumination.
Hoorelbeke, Vervaeke, et al. (2022)	PASAT (gamified)	10 sessions over two weeks	Yes	Trait repetitive negative thinking in a varied sample with elevated repetitive thinking	Trait repetitive negative thinking was lower following the training, but this reduction cannot specifically be linked to the EC training as there was no control group.
Hoorelbeke et al. (2016)	PASAT	10 sessions over two weeks	Yes	State rumination (measured 8 times a day during 7 days)	EC training was associated with reduced state rumination in response to low positive affect. There were no other effects of EC training on rumination.
Hoorelbeke et al. (2022)	PASAT	10 sessions over two weeks	No	State rumination (measured 6 times a day for four weeks)	EC training was associated with a reduced use of rumination over time when in a positive affective state, but not when in a negative affective state
Lass et al. (2021)	PASAT	6 sessions over two weeks	No	Trait rumination in students	EC training reduced depressive symptomatology but not trait rumination
Ferrari et al. (2021)	PASAT	10 sessions over two weeks	No	State rumination and trait rumination major depressed patients	No effect of EC training on either trait or state rumination

Reference	Type of training	Number of sessions and time span	Transfer on other tasks	Rumination outcome measure(s)	Main findings
Hoorelbeke et al. (2021)	PASAT	10 sessions over four weeks	Yes	Trait rumination in remitted depressed patients	EC training did not reduce rumination at one-year follow-up compared to the active control condition
Daches et al. (2019)	Negative affective priming task	5 sessions over three weeks	Yes	State and trait rumination in students	Reduced state rumination post-training and at a two-week follow-up following the recall of a negative personal event. There was no effect of the training on trait rumination.
Onraedt & Koster (2014)	Dual n-back task	6 sessions in six consecutive days	No	Trait rumination in undergraduates	The EC training had no effect on trait rumination and depression measures (post-training and at two-weeks follow-up).
Wanmaker et al. (2015)	Dual n-back task + Symmetry Span	24 sessions (6 sessions a week during four weeks)	Mixed	Trait rumination in patients with depression and/or anxiety	The EC training did not reduce trait rumination
Daches & Mor (2014)	Negative affective priming task	4 sessions over two weeks	Not measured	Trait rumination in students	Improved EC was not associated with reduced rumination
Pan et al. (2020)	Emotional and non-emotional dual n-back task (mobile-based)	21 sessions during 21 days	Yes	Trait rumination in anxious individuals	Both forms of EC training led to improved WM capacity, updating, and shifting. Both forms of EC training were associated with reduced trait rumination at one-month follow-up, compared to the control condition.
Roberts et al. (2021)	Newly developed adaptive working memory updating task	20 online training sessions	Yes	State rumination in response to a stressor in young people (16-24 years old)	Significant decrease in state rumination post-training compared to non-adaptive training, but only in the training condition with neutral stimuli (not in the condition with negative stimuli). No evidence that trait rumination moderates the effect of EC training.
Cohen et al. (2015)	Flanker Task	Single session	Not measured	State rumination following the recall of an upsetting event in students	Participants in the EC training condition had lower state rumination compared to the control group
De Putter et al. (2015)	Dual n-back task	Single session	Yes	State rumination in healthy participants	No improvement in state rumination after a rest period

Reference	Type of training	Number of sessions and time span	Transfer on other tasks	Rumination outcome measure(s)	Main findings
Quinn et al. (2014)	Adaptive n-back task	Single session	Not measured	No measure of rumination, only a measure of cortisol as a measure of reactivity to stress in students	Only participants that were high in trait rumination had a reduction in salivary cortisol
Daches et al. (2015)	Negative affective priming task	Single session	Yes	State rumination in students	No effect of EC training on state rumination.
Yu et al. (2020)	EEG Neuro-feedback	20 sessions over 10 weeks, 2-3 times per week	Yes	Trait rumination in dysphoric students	The neuro-feedback EC training enhanced EC (i.e., updating) and reduced trait rumination.

Note. EC = Executive control; PASAT = Paced Auditory Serial Addition Task.

2.3.4 Summary of the research on the associations between rumination and executive control

The relationship between rumination and executive control has been extensively studied using correlational, longitudinal, and experimental designs (see Table 5 for a summary). Meta-analyses of cross-sectional studies suggest an association between increased trait rumination and worse executive control. However, the strength of this association is small at best, varies across studies, and depends on the specific executive functions being assessed. The overall picture is complex, with some meta-analyses indicating no significant correlation between rumination and overall executive functioning.

Prospective studies, though limited in number and heterogeneous in design, suggest that impaired executive control may lead to increased trait rumination over time. However, there is insufficient research on the reverse direction of causation to exclude the possibility of a bidirectional or inverse relationship—only one study investigated whether trait rumination leads to worse executive control over time.

Experimental research has been instrumental in studying the effects of state rumination on executive control, thereby testing the resource depletion account. Some studies suggest that inducing state rumination can impair executive control, but findings are inconsistent. The inconsistencies might be due to factors such as the method of rumination induction, the specific executive function being assessed, the tasks employed for measurement, and the type of population studied (e.g., depressed, dysphoric, or control participants). While inconclusive, these results provides tentative support for the resource depletion account proposing state rumination taxes cognitive resources needed for executive control.

Meanwhile, executive control training, such as cognitive control training (CCT) and neurofeedback, has demonstrated effectiveness in reducing both state and trait rumination in some studies, supporting the idea that executive control plays a causal role in rumination. High heterogeneity among studies is due to the different types of control conditions (active vs. no-training control conditions), how rumination is measured and when, the sample type, and the different types of executive control training used, including the Paced Auditory Serial Addition Task (PASAT) and other types of training such as dual n-back tasks and neurofeedback. Overall, while some results are promising, further research is needed to examine the long-term effects of executive control training and the nuances between its effects on state versus trait rumination.

In conclusion, the relationship between rumination and executive control is complex and not fully understood, particularly when considering the important distinctions between state and trait rumination. Cross-sectional associations between higher trait rumination and impaired executive control are small and do not inform about causality. A few heterogeneous prospective studies suggest a causal relationship, with impaired executive control leading to increased trait rumination, but the inverse causal relation was only examined in one study. Experimental findings provide inconsistent support for either the resource depletion account or the impaired disengagement hypothesis: induced state rumination can impair executive control and improving executive control with training can reduce trait and state rumination. These mixed and complex results make it difficult to draw definitive conclusions on the causal relationship between rumination and executive control. Hence, further research is needed to clarify these relationships, address current limitations in the field, and explore potential moderators of these effects.

Table 5. Summary of the research on the associations between rumination and executive control

Direction of Causality	Study Type	Rumination Type	Main findings & Limitations
EC – Rum	Meta-analyses and cross-sectional studies	Trait	Small associations found between rumination and several different executive functions. It is unclear whether all core executive functions are impaired or only certain ones. No moderating effect of stimuli's emotional valence found.
EC → Rum	Prospective research	Trait	Some studies found impaired executive control to be a significant predictor of increased rumination over time. High heterogeneity in studies; limited number of studies, varying time scales and tasks used to measure EC.
	Experimental research	State/trait	Most studies using an adaptive Paced Auditory Serial Addition Task found it reduced rumination after the training but not at follow-up. However, some results indicated a potential detrimental effect of improving EC. Mixed results for other types of executive control training. Limitations include the use of no-training control groups which might overestimate the effect of training, and task-specific learning effects which may not reflect an improvement in executive functioning.
Rum → EC	Prospective research	Trait	One prospective study found that baseline rumination predicted worse switching performance 15 months later. No other prospective study investigated this direction of causality.
	Experimental research	State	Mixed results: some studies found that inducing state rumination reduced executive control performance, while others found no significant effect. The effect seems to vary depending on the population and type of executive function measured.
Rum ↔ EC	Intensive longitudinal research	State	No study found to date.

Note. EC = Executive control. Rum = Rumination.

2.4 Exploring the neural basis of rumination and executive control

While research has extensively studied the relationship between rumination and executive control, the findings remain inconsistent. Small cross-sectional correlations, mixed experimental results, and unresolved questions of causality indicate a complexity in the relationship between these constructs. To resolve this heterogeneity, researchers turned their interest to studying the neurological underpinnings of executive control and rumination. Examining these neural circuits and substrates may shed light on the intricate dynamics between executive processes and ruminative thought patterns. The following sections aim to delineate some of the neurological foundations of executive control, explore the neural correlates of rumination, and discern how their interplay might explain the observed variability, particularly within the context of experimental neuromodulation studies.

2.4.1 Overview of the prefrontal cortex

The prefrontal cortex (PFC) has long been established as crucial part of the brain for executive functioning[5]. Early evidence of this link came from patients with PFC lesions who showed impaired judgment, planning, decision-making, that translated to difficulties regulating their behavior and emotions in everyday life (Fuster, 1997; Miyake et al., 2000; Stuss & Benson, 1984; Szczepanski & Knight, 2014). These observations and further research initially led researchers to hypothesize that whenever these impairments are present, they resulted from impairments in the prefrontal cortex. However, more recent research has found that such behavior involves not only the PFC but also interactions between the PFC and different cortical and subcortical areas (Miller & Cohen, 2001; Royall et al., 2002; Stoet & Snyder, 2009). Ongoing neuropsychological research further underscores the PFC as a central coordinator for regulating complex behavior (Baddeley, 1998; Friedman & Miyake, 2017; Soltani & Koechlin, 2022).

The literature on the neural underpinnings of executive functions encounters a debate that echoes the one about the unity/diversity in the measurement of executive functions discussed earlier. Some researchers argue for a 'multiple demand system,' encompassing frontal and parietal regions implicated in various complex tasks, suggesting a shared neural network (Duncan, 2010; Duncan & Owen, 2000; Fedorenko et al., 2013). This system engages during tasks that tap into one or several executive functions. This unitary view of the underlying neural circuits contrasts with other researchers' point of view that distinct brain regions support specific executive functions (e.g., Petrides, 2005; Stuss & Alexander, 2007). This ongoing discourse about the PFC's functional organization has been summarized by Friedman & Miyake (2017), who point out that while various theories emphasize different aspects of common versus specific functions, they collectively acknowledge the PFC's role in a broad range of executive tasks.

[5] It is likely any observation and measurement of executive control abilities result from a balance between top-down processes and bottom-up processes. However, this thesis focuses on the top-down aspect.

Reviewing all the research on the neurological underpinnings of executive control is beyond the scope of this section, especially since extensive reviews have been published recently, both on the prefrontal cortex specifically (Haber & Robbins, 2022) and on how the prefrontal cortex mediates executive functions (Friedman & Robbins, 2022). This broad spectrum of executive functions and the diverse neurological frameworks may be akin to the complex nature of ruminative thought processes. Just as the PFC manages various aspects of executive control, rumination too — as a goal directed and habitual thought process — could be influenced by multiple distinct neural pathways within this region. However, reviewing all the different brain regions potentially involved in rumination is also beyond the scope of this section.

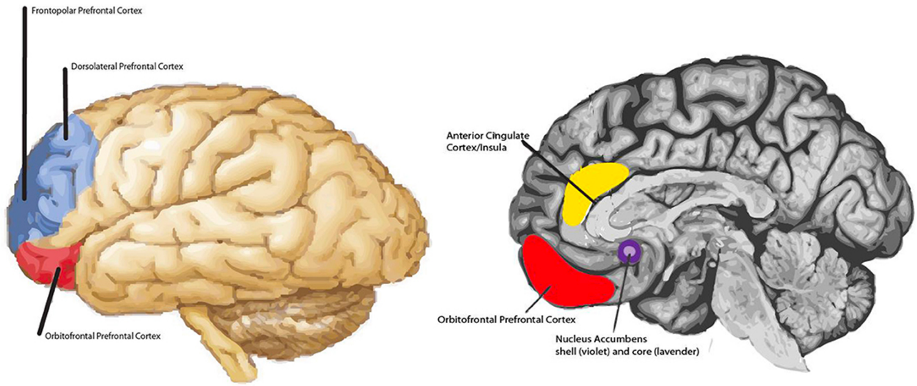
Instead, the next section focuses on the role of the dorsolateral prefrontal cortex (dlPFC), a key area within the PFC, that has been linked to executive control and rumination. By exploring this common neural substrate, the next sections aim to provide a clearer understanding of their intricate relationship. The subsequent sections will address how these shared neural pathways have been examined in both observational and neuromodulation studies, such as those utilizing tDCS.

2.4.2 The dlPFC: a key region for executive control and rumination

Rumination has been associated with several brain regions and networks. For instance, it has been associated with disturbed prefrontal-amygdala activity (Disner et al., 2011; Ochsner & Gross, 2005; Ray et al., 2005) and abnormal connections between the frontal lobe and the default mode network (DMN; Hamilton et al., 2015). Among the many brain regions investigated, the dorsolateral prefrontal cortex (dlPFC; see Figure 2) has been identified as a critical region involved in both domain-general executive functions and for rumination specifically.

The dlPFC is a functionally heterogenous brain region (Glasser et al., 2016) and considered a part of a broader 'cognitive control network,' comprising the dlPFC, the medial frontal cortex (including the anterior cingulate cortex [ACC]), the parietal cortex, the motor areas, and the cerebellum (Bellebaum & Daum, 2007; Braver & Barch, 2002; D'Esposito, 2007; Fuster, 2002). It is involved in the maintenance of task-relevant information and goal representations in a context-dependent manner (Badre & Nee, 2018; Brass et al., 2005; Chambers et al., 2009; de la Vega et al., 2018; Dosenbach et al., 2008; Petrides, 2005). More specifically, the dlPFC monitors signals from internal and external sources, highlighting those that are the most relevant to current goals (Jiang et al., 2018; Petrides, 2005). Moreover, it plays an important role "in the process of prioritizing cognition that matches the demands of a particular context" (Turnbull et al., 2019, p. 6).

Figure 2. The dorsolateral prefrontal cortex



Note. This Photo is licensed under CC BY (Light, 2019).

Additionally, the dlPFC is thought to mediate the core executive functions (Duncan & Owen, 2000; Miller & Cohen, 2001). Indeed, it has consistently been associated with EFs: updating/working memory (Barbey, Koenigs, et al., 2013; Sandrini et al., 2008; E. E. Smith & Jonides, 1997), shifting (Konishi et al., 1998; Luna et al., 2015), and has been found to be involved more broadly in tasks requiring working memory, inhibiting irrelevant information, and selecting competing task-relevant responses, as reflected in the involvement of the dlPFC in the performance of anti-saccade trials (Funahashi, 2001; Johnston & Everling, 2006; Wegener et al., 2008), selective response inhibition (Garavan et al., 2006; Simmonds et al., 2008) and response selection (Braver et al., 2001; Rowe et al., 2002).

The dlPFC has also been associated with broader constructs: divergent thinking/creativity (Liu et al., 2015), decision making (Philiastides et al., 2011; Rahnev et al., 2016), value encoding (Botvinick & Braver, 2015; Kouneiher et al., 2009; Sokol-Hessner et al., 2012), and emotion regulation (Buhle et al., 2014; Etkin et al., 2015; Frank et al., 2014; Okon-Singer et al., 2015; Treadway et al., 2014). As summarized by Niendam et al. (2012) in their meta-analysis, the dlPFC supports one's ability to orient attention depending on task demands, to maintain rules for action, and to efficiently select responses, whereas "parietal activation is considered to provide the dlPFC with information on stimulus salience and learned stimulus-response pairings" (Niendam et al., 2012, p. 256).

Given the important role the dlPFC has, it has been widely studied in the context of psychopathology and impaired executive functioning. The left and the right dlPFC are strongly connected, creating an 'interhemispheric balance', essential for healthy executive function. Several psychopathological conditions known for presenting impaired executive functioning can display an interhemispheric imbalance, manifesting as a hypoactivation of the left dlFPC or sometimes as a hyperactivation of the right dlPFC: for instance, major depression (Grimm et al., 2008; Koenigs & Grafman, 2009; Salehinejad et al., 2017), panic disorder (Mantovani et al., 2007), or attention-deficit hyperactivity disorder (Christakou et al., 2013; Nejati et al., 2020; Salehinejad et al., 2017). Moreover, neuromodulation studies have further underscored the role of the dlPFC in executive control by showing that modulating dlPFC's activity can enhance executive control in both healthy (Brunoni & Vanderhasselt, 2014; Salehinejad et al., 2017) and clinical samples (Salehinejad et al., 2017; Wolkenstein & Plewnia, 2013).

Several studies support the association between higher rumination, impaired executive control, and lower activity in the dlPFC (Koster et al., 2011). Findings from neuroimaging research have lent strong support to the involvement of the dlPFC in rumination (Cooney et al., 2010; Forster et al., 2015), with EEG studies demonstrating hypoactivation of the left dlPFC in high ruminators (Ferdek et al., 2016). This suggests a mechanism by which people with a tendency to ruminate may struggle to regulate negative affect and emotions, possibly also due to impaired connectivity of the dlPFC with regions (Olson et al., 2007).

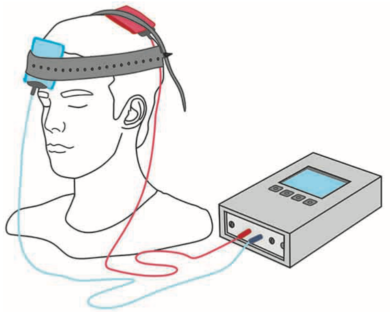
Continuing with this line of inquiry, the next section will introduce transcranial Direct Current Stimulation (tDCS) as a method to explore the dlPFC's influence on executive functioning and rumination. This section will examine evidence from tDCS studies that suggest that stimulating the dlPFC not only improves executive control but may also reduce rumination, shedding light on the potential of this region to act as a proxy for executive control.

2.5 The impact of Transcranial Direct Current Stimulation on executive control and rumination

With the dlPFC's pivotal role in executive functioning and rumination established, this section highlights the potential of transcranial Direct Current Stimulation (tDCS) to further our understanding. This non-invasive brain stimulation method offers a window into the causal relationships between neural activity and cognitive processes, providing a promising avenue for probing the neural substrates that underlie the complex interplay between executive control and ruminative thoughts.

2.5.1 TDCS mechanisms and important parameters

Figure 3. Transcranial Direct Current Stimulation Illustration



Note. Two tDCS electrodes are placed on the scalp of a subject. The red electrode is the anode whereas the blue electrode is the cathode. This Photo is licensed under CC BY (Yavari et al., 2017).

Transcranial Direct Current Stimulation has gained prominence as both an experimental research tool and a potential therapeutic instrument, particularly in its application to the dorsolateral prefrontal cortex (dlPFC), which plays a significant role in executive control and rumination. It is a non-invasive brain stimulation technique that modulates neuronal excitability and plasticity, and consists of the application of a weak direct electrical current (e.g., 1—2mA) through two or more electrodes placed on the scalp between which the current flows (Nitsche et al., 2008). This electric stimulation induces a subthreshold modulation of neuronal membrane potentials, which alters cortical excitability (Bikson et al., 2019). It does not induce activity in resting neural networks but modulates cortical excitability, plasticity, and functional connectivity by interacting with concurrent brain activity (Fritsch et al., 2010; Nitsche et al., 2008).

Importantly, tDCS influences neuronal excitability in a polarity-dependent manner: an anode is expected to produce depolarization of the pyramidal neuron soma, which may increase excitability, whereas a cathode will produce soma hyper-polarization, decreasing excitability (Radman et al., 2009). For example, consistent data shows that anodal stimulation of the dlPFC combined with a working memory task improves performance (M. E. P. Berryhill et al., 2014;

Brunoni & Vanderhasselt, 2014). The opposite might be expected from cathodal stimulation. However, this is not always the case, as Batsikadze et al. (2013) results show that applying a 2 mA cathodal stimulation for 20 min resulted in cortical excitability enhancement instead of inhibition. Indeed, a meta-analysis by Jacobson et al. (2012) demonstrated that the effects of cathodal stimulation are more inconsistent than those of anodal stimulation, particularly its effect on cognition.

The parameters of tDCS, including electrode placement, size, and montage, significantly affect the outcomes (see Figure 3 for an illustration of a tDCS machine and a montage of electrodes). For instance, electrode size influences current density applied to the scalp (Nitsche et al., 2008), and montage determines the current flow through the brain, impacting tDCS-induced effects. The montage used varies depending on whether the reference electrode is placed in an extra-cephalic position or a cephalic region; the montage can also be 'bi-hemispheric': it consists in placing the two electrodes on the targeted region, one electrode on each hemisphere respectively (e.g., on the left dlPFC and the right dlPFC). The tDCS montage is important as it affects the current flow through the brain and induces variability in results when comparing different montages (Nitsche et al., 2008). For example, one study showed that the distance between two electrodes impacts the duration and the magnitude of tDCS-induced after-effects (Moliadze et al., 2010). Many other studies have found that differences in either the active electrode positioning or the reference positioning/size can impact tDCS's effects (DaSilva et al., 2011; Penolazzi et al., 2013; Wörsching et al., 2018).

The duration, stimulation intensity, and number of sessions are also key parameters. For example, the effects of a 10 min stimulation of tDCS (at 1 mA) last up to 50 min after the stimulation regardless of tDCS polarity (Lang et al., 2005) whereas longer or more intensive stimulation does not necessarily increase tDCS's efficacy (Batsikadze et al., 2013; Cuypers et al., 2013; Esmaeilpour et al., 2018; Jamil et al., 2017; Karuza et al., 2016). Moreover, modulatory effects of tDCS can accumulate when tDCS is applied in consecutive sessions (Alonzo et al., 2012; J. Reis et al., 2009; Waters-Metenier et al., 2014). However, when the aim is to study the effect of a single session of tDCS stimulation, it is warranted to consider the interval between sessions. In a meta-analysis, Dedoncker et al. (2016b) found that the interval between sessions did not influence the estimated effect size. However, this might be the case when comparing an active condition to a sham condition. When comparing two active conditions, Alonzo et al. (2012) recommend using an interval of at least 48 h (an interval of one week should avoid interferences). In line with this, Monte-Silva et al. (2010, 2013a) results show that a 24h break is insufficient.

State-dependency is another critical aspect that might explain the interindividual and intraindividual variability observed in studies. State-dependency refers to the phenomenon that occurs when "the impact of any external stimulus is dependent on the properties of that stimulus but also the initial state of the stimulated system" (Silvanto et al., 2008, pp. 452–453). Dubreuil-Vall et al.'s (2019) results are an example of physiological state-dependency of tDCS: tDCS led to greater modulation of participants' physiology and behavior among the participants with baseline physiological states characteristic of less adaptive processing of information. Additionally, different levels of fatigue, sleep or wakefulness, drug-free or dosed, novice or expert, are some of the many factors and interindividual differences (impacted by factors such as age, mental health, and diseases) involved in state-dependency (for reviews, see Liu et al., 2015; Silvanto et al., 2008).

These factors concern the system's state prior to any stimulation, but state-dependency also comprises the different characteristics of the stimulus and task interacting with the system's characteristics during the stimulation (Shah-Basak et al., 2019; Woods et al., 2016). Task difficulty is one of these characteristics. In a study by Hsu, Juan, & Tseng (2016), only the optimal level of task difficulty revealed any significant tDCS effect. This study replicated similar results by Jones & Berryhill (2012). Another example is that anodal tDCS over the left dlPFC enhanced the ability to solve difficult verbal insight problems, but no effects were found for easy problems (Metuki et al., 2012). Thus, when there is no effect of tDCS on the performance on an online task, this could mean that the task may have been too easy or that the participants' skills were too high. In other words, the (lack of) tDCS effects might be explained by ceiling effects in performance measures (Furuya et al., 2014), differences in cognitive load involved in the task (e.g., Gill et al., 2015), or the timing of the task relative to the stimulation period (e.g., Nozari et al., 2014). Finally, some studies indicate that ensuring that participants' incentives are high improves the effectiveness of tDCS (Di Rosa et al., 2019; K. T. Jones et al., 2015).

The implications of the influence of all these factors are profound. They suggest that to maximize the efficacy of tDCS and interpretability of its effects, one must consider not only the technical parameters of tDCS but also the participant's physiological and psychological state, which includes any activity they might be subjected to before, during, or after tDCS.

2.5.2 Effects of tDCS on executive control

For many decades, transcranial electric stimulation techniques such as transcranial Direct Current Stimulation (tDCS) have been used to study the function of cortical areas and modulate brain activity. In the last couple of years, there has been an increase in interest in clinical applications of tDCS in many fields, such as neurology and psychiatry (Brunoni et al., 2012). For example, tDCS has been used to improve the vigilance of sleep-deprived participants (J. T. Nelson et al., 2014) and to improve cognition in age-related dementia (W.-Y. Hsu et al., 2015). Moreover, tDCS has also been used in clinical psychology to investigate its effect on mental disorders such as major depressive disorder and general anxiety disorder (Moffa et al., 2020; Razza et al., 2020). Several systematic reviews and meta-analyses of randomized controlled trials indicated the safety and therapeutic efficacy of tDCS for a wide range of mental disorders (for a review, see Tortella et al., 2015), including, among others, depression and mood disorders (Borrione et al., 2018; Dondé et al., 2018; Razza et al., 2020), anxiety disorders (Stein et al., 2020; Yosephi et al., 2019), psychotic disorders (E. H. M. Lee et al., 2018), pain-related disorders (Zortea et al., 2019), and eating disorders (Dalton et al., 2018). Hence, TDCS quickly arose as a promising therapeutic tool.

Several studies investigated the impact of tDCS in improving executive control (most often by stimulating the dlPFC). Overall, results from single studies are promising. Anodal tDCS over the left dlPFC significantly improved executive functions: task switching (Alizadehgoradel et al., 2020; Enriquez-Geppert et al., 2013; Leite et al., 2011; Wang et al., 2020), updating (Alizadehgoradel et al., 2020; Fregni et al., 2005; Ohn et al., 2008; Zaehle et al., 2011), and working memory (Alizadehgoradel et al., 2020; Brunoni & Vanderhasselt, 2014; Salehinejad et al., 2015).

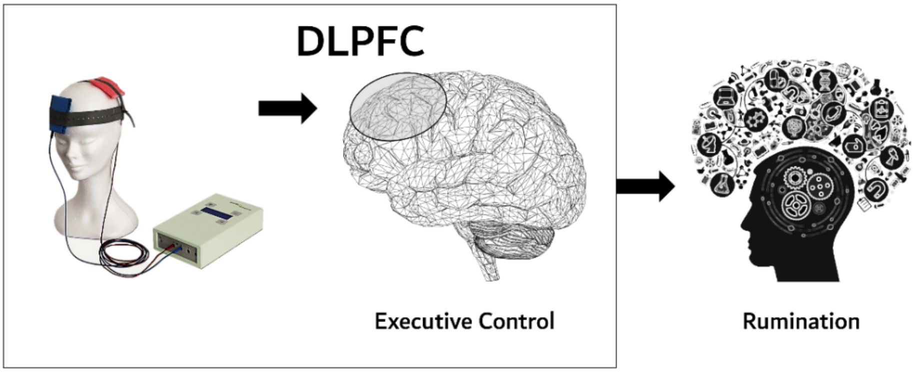
Importantly, several reviews have summarized the existing evidence relating to the impact of tDCS on executive functioning. Strobach and Antonenko's (2017) narrative review demonstrates that tDCS successfully alters and improves all executive functions. More specifically, anodal tDCS over the left dlPFC improved updating and shifting, whereas anodal tDCS over the right dlPFC improved inhibition. Yet, two recent meta-analyses investigated the effect of tDCS in patients with brain disorders (Begemann et al., 2020) and healthy controls (de Boer et al., 2021) and found more nuanced results. In people with brain disorders (e.g., schizophrenia, depression, dementia, Parkinson's disease, stroke, traumatic brain injury, and multiple sclerosis), tDCS compared to sham stimulation significantly improved working memory—although it was a small effect with no differences across types of brain disorder ($k = 28$; $n = 939$; $ES = 0.17$, $p = 0.021$)—but not executive functioning ($k = 19$, $n = 662$, $ES = 0.04$, $p = 0.726$) (Begemann et al., 2020). In healthy controls, tDCS had no significant effect on working memory or working memory updating (e.g., using the N-back task) (de Boer et al., 2021). However, tDCS had a significant effect on tasks requiring motor inhibition (e.g., Go/No go task) (de Boer et al., 2021), but not on tasks that require suppression of prepotent responses when incongruent stimuli are presented (i.e., the flanker task and Stroop task).

The results regarding working memory are in line with two previous meta-analyses (Horvath et al., 2015; Mancuso et al., 2016) but not with meta-analyses that found small (Brunoni & Vanderhasselt, 2014; Hill et al., 2016) to medium effect sizes (Imburgio & Orr, 2018). Various methodological discrepancies in the design of the meta-analyses might explain these different results: for example, different inclusion criteria (e.g., only studies that stimulated the dlPFC specifically), differences in included tasks, the distinction between single and multiple sessions, and whether authors examined task-specific effects. Moreover, the interpretation of the results of systematic reviews and meta-analyses related to executive control is limited by how it is defined and how tasks are classified—echoing the jingle-jangle fallacies introduced in the beginning of this chapter. For instance, working memory can refer to working memory capacity or working memory updating; other authors might even consider that if there is no manipulation of information involved, it is not referring to working memory. An example of the limitations of classification for tasks is the N-back task: it is typically used to measure the updating executive function but is also more broadly referred to as a working memory task. Hence, reviews about working memory that include N-back tasks are also indicative of tDCS' effect on updating abilities. Overall, evidence indicates that tDCS might be beneficial for clinical subjects suffering from deficits in executive control. Regarding healthy subjects, the effect of tDCS on executive control is unclear and small at best. Lastly, for both clinical and healthy samples, the variety of parameters involved in tDCS studies, and the ensuing heterogeneity make any conclusions complicated and tentative at best.

2.5.3 Effects of tDCS on rumination

Nevertheless, some researchers investigated whether tDCS could directly impact rumination. Indeed, several findings support such a hypothesis: rumination has been linked to worse executive control, which is associated with a hypoactivation of the left dlPFC; tDCS could enhance executive control, especially through anodal stimulation of the left dlPFC; and tDCS seems to help treat depression, which is a mental disorder typically characterized by ruminations. Hence, considering previous research, tDCS could be used either as a clinical tool to influence rumination (e.g., in the context of depressive patients) or to examine the role the dlPFC and executive control play in rumination (see Figure 4).

Figure 4. The dlPFC as a proxy of executive control through which TDCS' impacts rumination



Note. This figure illustrates how rumination could be manipulated through changes in executive control by stimulating the dlPFC with tDCS.

The first studies were published in 2013; since then, a handful more have been published. Some studies focused on healthy participants only. For instance, Vanderhasselt et al. (2013) found that anodal tDCS, compared to sham stimulation, over the left dlPFC did not influence state rumination. However, the effect of the anodal stimulation on state rumination was mediated by improvements in shifting away from negative material in a working memory task. Additionally, this mediation effect was moderated by trait rumination: the higher trait rumination was, the more pronounced this mediation was. Hence, it is possible that tDCS' effect on state rumination, and the mediation effect through improvements in shifting abilities, is absent in low ruminators and only present in high ruminators. In a sample of female students, anode over the left dlPFC significantly reduced state rumination compared to sham stimulation (Baeken et al., 2017). This significant reduction in state rumination was associated with increased perfusion in the dlPFC: which could indicate that anodal tDCS over the left dlPFC facilitated the recruitment of the left dlPFC, which helped participants ruminate less (e.g., through better executive control or better emotional processing). Similarly, in a sample of healthy female participants, anodal tDCS over the left dlPFC significantly reduced state rumination (De Raedt et al., 2017). In contrast, in a healthy sample, Voss et al. (2018) did not find an effect of anodal tDCS over the left dlPFC on state rumination after watching a trauma film. Lastly, only one study explored whether tDCS could increase rumination in a sample of healthy participants. Anodal tDCS on the right dlPFC (with the cathode on the left dlPFC) increased state rumination after an anger-inducing manipulation, whereas anodal tDCS on the left dlPFC (and the cathode on the right dlPFC) and sham stimulation did not affect rumination (Kelley et al., 2013).

Some studies investigated whether tDCS over the dlPFC could enhance executive control training and thereby help reduce rumination. One study on a healthy sample found no effect of tDCS nor training (whether combined or not with executive control training) on state rumination (De Putter et al., 2015). In a sample of major depressed patients, executive control training significantly reduced rumination post- vs. pre-intervention, but tDCS did not lead to further improvements (Vanderhasselt et al., 2015).

In summary, tDCS studies have sparked a strong interest in the use of tDCS as a new therapeutic tool to treat rumination. Yet, only a few studies directly investigated this effect, and the results are mixed. Thus, uncertainty remains regarding the ability of tDCS to yield a reliable and robust impact on rumination.

2.6 Summary and conclusion

The primary aim of this chapter was to give a comprehensive overview of the research on the relationship between executive control and rumination by contrasting the findings against two main theories: the impaired disengagement hypothesis and the resource depletion account. The impaired disengagement hypothesis posits that deficits in executive control lead to difficulties disengaging from negative thoughts, contributing to sustained rumination. In contrast, the resource depletion account suggests rumination consumes cognitive resources needed for executive control, thereby impairing performance on concurrent tasks requiring executive functions.

Cross-sectional studies reveal a small association between impairments in executive functions and a higher tendency to ruminate. However, findings vary across studies and meta-analyses, and causation cannot be determined from correlational data. Longitudinal studies provide preliminary support that deficits in executive control may contribute to increased trait rumination over time, in line with the impaired disengagement hypothesis. Moreover, experimentally improving executive control through training appears to reduce state and trait rumination, thereby lending credence to the causal role of executive deficits as proposed by the impaired disengagement hypothesis. However, findings are inconsistent across diverse training protocols. Meanwhile, experimental studies that induced rumination among participants yield mixed results regarding state rumination's causal effect on executive control, providing only tentative support for the resource depletion account.

The association between rumination and executive control has been further studied with transcranial Direct Current Stimulation by investigating the effect of stimulating the dlPFC (a region involved in both rumination and executive control). Only a handful of studies were conducted. Results are mixed, with some studies finding an effect of tDCS on state rumination (De Raedt et al., 2017), while others found no effect (Voss et al., 2018), and some even found that executive control training successfully reduced rumination but that tDCS did not have any additional benefits (Vanderhasselt et al., 2015). Reasons for these inconsistencies remain unclear.

In summary, while there is evidence for a small association between impaired executive control and increased rumination, the relationship is complex and definitive conclusions are hindered by the heterogeneity across study methodologies. Key questions remain regarding the cognitive mechanisms linking state versus trait rumination to executive control deficits, the influence of individual differences, and how best to unravel the nuances of this relationship. Rigorously designed longitudinal experiments and interventions are critical to further elucidate the causal interplay between executive control and rumination. Given the clinical relevance of both rumination and executive control, advancing understanding of their interplay has important implications for developing effective treatments.

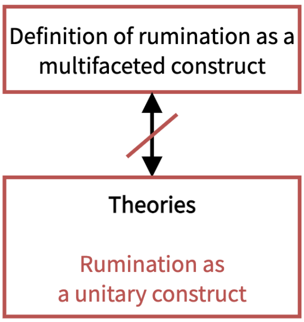
Chapter 3.

Interlude on the limitations of the reviewed literature

The preceding chapters covered a broad literature about research on rumination. The first chapter reviewed how rumination has been conceptualized, describing the most prominent theories and associated research. The second chapter honed in on the role of executive control in rumination, reviewing theoretical hypotheses and supporting empirical evidence. In addition to these insights, the chapters underscore ongoing uncertainties in rumination research, particularly concerning its causal mechanisms. For instance, the interplay of mechanisms in the HEXAGON model remains obscure, limiting our understanding of its broader implications. Furthermore, the evidence for executive control's causal influence on rumination is predominantly correlational, thus tentative. Although some progress has been made, most of the limitations and uncertainties related to rumination research and its associations with executive control have not changed much in the last ten years. Hence, the theoretical progress in understanding rumination has been overall slow with no major breakthroughs. This slow progress could be due to several problems and these problems can occur at several stages of the scientific process.

3.1 First limitation

Figure 5. Disparity between definition of rumination and theories

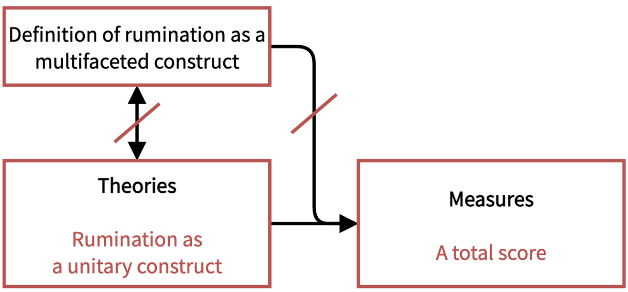


Note. Although definitions of rumination comprise various characteristics, the theories about rumination conceptualize it as a unitary construct and do not integrate the various characteristics of rumination in their conceptualization.

The first problem in rumination research occurs at the conceptual level (see Figure 5). Rumination is often defined as a thought process comprising different characteristics. For instance, Nolen-Hoeksema's (2008) definition and discussion of rumination refers to characteristics such as the valence of thoughts (i.e., negative), how self-critical thoughts are, their repetitiveness, and the extent to which one thinks about the causes and consequences of their symptoms. The HEXAGON model refers to an abstract processing style in contrast to a more concrete thinking style. The Repetitive Negative Thinking framework sought to investigate the differences and similarities in features of repetitive types of thinking such as worry and rumination (Ehring & Watkins, 2008). Yet, these different characteristics are almost never part of the constitutive elements of theories of rumination: most often the hypotheses of theories consist of "variables X, Y, Z cause rumination" or "rumination causes variables X, Y, Z". For example, the Response Styles Theory (Nolen-Hoeksema et al., 2008) does not refer to the different characteristics of rumination. The HEXAGON model includes the differentiation between an abstract thinking style versus a concrete thinking style (Watkins & Moulds, 2005), but several other features of rumination are ignored. Hence, existing theories did not integrate the different features of rumination (Ehring & Watkins, 2008; Gustavson et al., 2018) in their theoretical explanations and theorized about rumination as a unitary construct.

This issue at the theoretical/conceptual level partially causes problems at the measurement level. Because scientific theories serve as a guide for the other stages of research, this unitary view of rumination is reflected in how rumination has been measured so far (see Figure 6). The most common measure, the Ruminative Response Scale (RRS; Treynor et al., 2003), is generally used through a total sum-score of all the items, or at most two scores referring to a more maladaptive type of rumination (i.e., brooding) in contrast to a more adaptive type of brooding (i.e., reflection). Even research specifically focused on the various features of rumination lead to the development of a questionnaire with items referring to different features but that is only used through a total sum score (i.e., the Perseverative Thinking Questionnnaire (PTQ); Ehring et al., 2011).

Figure 6. Measures of rumination follow the unitary conceptualization of rumination

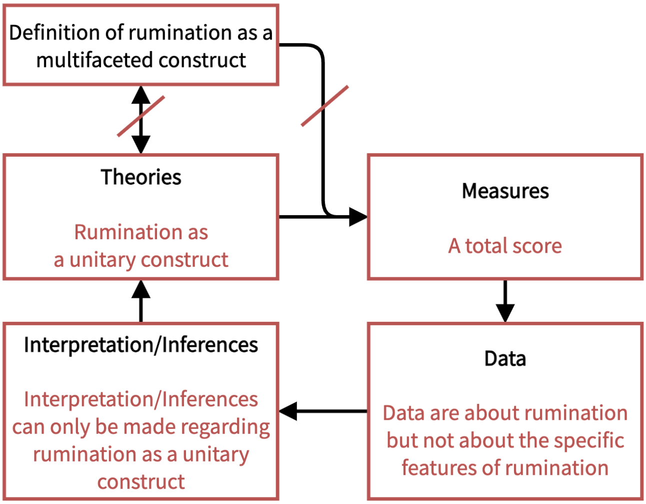


Note. Most rumination measures rely on theories that view rumination as a unitary construct. Therefore, these measures only provide a total rumination score.

"The answers you get depend on the questions you ask"
Thomas S. Kuhn[1]

This measurement of rumination through a single total score causes in turn problems at the theoretical level. Measuring rumination as a total score does not provide detailed information about the different features of rumination and their associations with other constructs. Consequently, the information (i.e., data) researchers have access to only allow them to interpret results regarding rumination as a unitary construct; they can only draw parallels with existing theories. Given that the assumptions of the theories are baked in the measures used to test the theories, the inferences researchers make cannot break that assumption and therefore the information they have at their disposal can only update their theories in a limited way. Hence, by lumping all the different features of rumination together into a single score, and measuring rumination in this way, researchers may have closed the door to finding more nuanced results involving specific features of rumination. Such granular results about the role of specific features of rumination might be one of the key missing ingredients for rumination theories to be further specified. In this sense, rumination theories are incomplete. Figure 7 shows a summary of this issue.

Figure 7. How a unitary conceptualization of rumination impacts research



Note. Given that rumination is studied as a unitary construct and measured as such, data collected about rumination only enables inferences about rumination as a unitary construct.

[1] I could not find the source of this citation. It is possible that it is a paraphrase of Thomas Kuhn's work. For instance, we can find the essence of this idea in his book *The Structure of Scientific Revolution*: "*[…] they discover that additional research makes it harder, not easier, to answer questions […]. Increasingly, a few of them suspect that these are simply the wrong sorts of questions to ask*" (Kuhn, 1996, p. 2).

3.2 Second limitation

A second problem in research on rumination might be a disparity between the research methods and the theory. Regardless of whether the theories or measurements are flawed or not, inadequate methodologies to test the theories could also lead to theoretical stagnation. Within this context, an inadequate methodology is anything that does not directly test the hypotheses of a theory. For instance, if a theory postulates that X causes Y, investigating correlations between X and Y are not direct tests of this hypothesis. A linear correlation between X and Y only means that they *could* be causally related, but it could also be a spurious association. Moreover, the absence of a linear correlation does not exclude a causal link (e.g., changes of a variable Y in response to changes of X could be non-linear). Even though a reliance on correlational research could stem from practical challenges (e.g., resource constraints, ethical considerations), it does not change the fact that they do not lead to theoretical breakthroughs.

In the context of research on rumination, even though most researchers and theories assume that rumination fluctuates over time, this dynamic aspect of rumination has not been investigated enough. Indeed, the theories of rumination presented so far share broad similarities; they all assume to some extent that (1) rumination is a psychological process that has various features (e.g., valence, repetitiveness, automaticity), (2) rumination fluctuates over time (e.g., it can get triggered by a goal discrepancy and can continue until the perceived discrepancy is reduced or something else requires our immediate attention), and (3) time is a crucial element of the consequences of rumination (e.g., can become a habit if used repeatedly over time and induces negative physiological changes). Yet, this element of time, the dynamic aspect of rumination, has not been the focus of most studies.

Research on rumination mainly measured rumination at a trait-level either at a single time point or measured over months and years, with most studies being cross-sectional or longitudinal. Rumination has also been studied as a state, but mostly at a single time point in experimental studies. Neither capture the temporal fluctuations of rumination across hours or days. For instance, existing efforts of meta-analyses and systematic reviews rely heavily on studies that used trait questionnaires. These meta-analyses established associations between rumination and diverse psychological phenomena: perfectionism (i.e., rumination was found to be positively correlated to perfectionism and to mediate the relationship between perfectionism and distress; Xie et al., 2019); sleep (i.e., worse sleep quality, shorter total sleep time, and longer sleep onset latency were all associated with a higher tendency to ruminate; Clancy et al., 2020); risky health behaviors (i.e., increased rumination was associated with increased risky health behaviors, such as substance use, alcohol consumption, unhealthy eating, and smoking; Clancy et al., 2016). Prospective studies also established strong relationships using trait measurements: for example, rumination predicted depression a month later (Mills et al., 2014), and co-variation of stressful events and ruminative thinking predicted depression 15 months later (Vanderhasselt et al., 2016); higher baseline rumination levels also predicted executive functioning impairments 15 months later (Connolly et al., 2014); and, rumination following trauma was found to predict the severity of posttraumatic stress symptoms from 2 months up to 4 years later (Moulds et al., 2020).

And experimental studies in which, for instance, state rumination is measured during a resting period, mostly served to correlate the extent to which people ruminated to other variables, be it psychological, neurological, or biological.

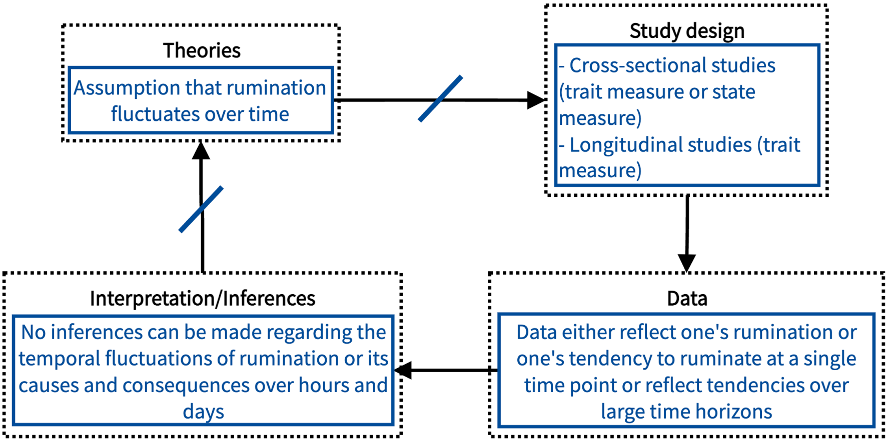
Hence, the bulk of rumination research mainly describes group differences (e.g., 'high' vs. 'low' ruminators) and their correlations with other constructs based on rumination being measured at a single time point or over large horizons of time. Although insightful in some regards, this focus on group differences/categorization and on measuring rumination at a single time point or only few time points is also problematic. Despite the cumulative knowledge acquired, this type of research does not allow us to understand *why* we observe such effects. Moreover, little is known about the fluctuations of rumination over shorter timeframes (minutes, hours, days). Just as with the issue related to measurement, studying rumination in this way does not provide enough empirical information that could feed into theories. This leaves the direct investigation of rumination's initiation and temporal development, and its causal mechanisms in everyday life, largely unexplored.

Additionally, using trait measures has many downsides. Trait measures intend to measure stables dispositions or tendencies over a specific period, yet, these assessments may obfuscate a complex reality. Research has shown that core symptoms of psychopathology, such as depressed affect, can be quite variable when measured using state measures (Barge-Schaapveld et al., 1999) and that correlations between repeated state measurements of pain, depression, anxiety, and fatigue, and (retrospective) trait measures of the same constructs are low (Turk et al., 2007). Moreover, results from a meta-analysis on the associations between rumination and sleep quality suggest that some trait measures used in cross-sectional studies might overestimate the strength of the associations due to response-bias compared to daily diary studies (Clancy et al., 2020). Likewise, social desirability might lead to self-report measurements under-estimating associations (Chan, 2008). Such results have led some researchers to suggest avoiding cross-sectional research because it lacks contextual information (e.g., Carver & Connor-Smith, 2010), although other researchers highlight that the relevance of using momentary assessments or global recollections depends on the questions asked (Shiffman et al., 2008). Hence, the bulk of the literature has focused on global recollections, that is, trait measures of rumination at a single or few time points, which lack contextual information, are subject to recall bias (Varese et al., 2019), and might be subject to over- or under-estimating the strength of associations.

Finally, an advantage of intensive longitudinal designs (with state measures) is that it allows to observe the impact of changes in variables of interest without having to manipulate those variables of interest. The golden standard to investigate causal associations is to manipulate a variable and see the effect of that manipulation on another variable. This is the case, for example, for the executive control training studies that sought to investigate the impact of changing executive control through training on rumination. However, sometimes manipulating a variable is not easily accomplished or might not be ethical. For instance, it would not be considered ethical to conduct a study in which researchers lower participants' executive control over time to see the impact on their tendency to ruminate. Therefore, intensive longitudinal studies with state measures offer an ethical and more ecological alternative to variable manipulation, while still allowing researchers to investigate causal associations between variables but through naturally occurring changes.

In summary, theories of rumination at least implicitly assume that rumination fluctuates over time, yet this fundamental assumption is not reflected in the study design choices (see Figure 8). Therefore, the data does not allow researchers to directly make inferences about the temporal fluctuations of rumination, nor their causes and consequences. This hinders further theoretical development as the temporal aspects of rumination are not used to better understand it and improve the theories.

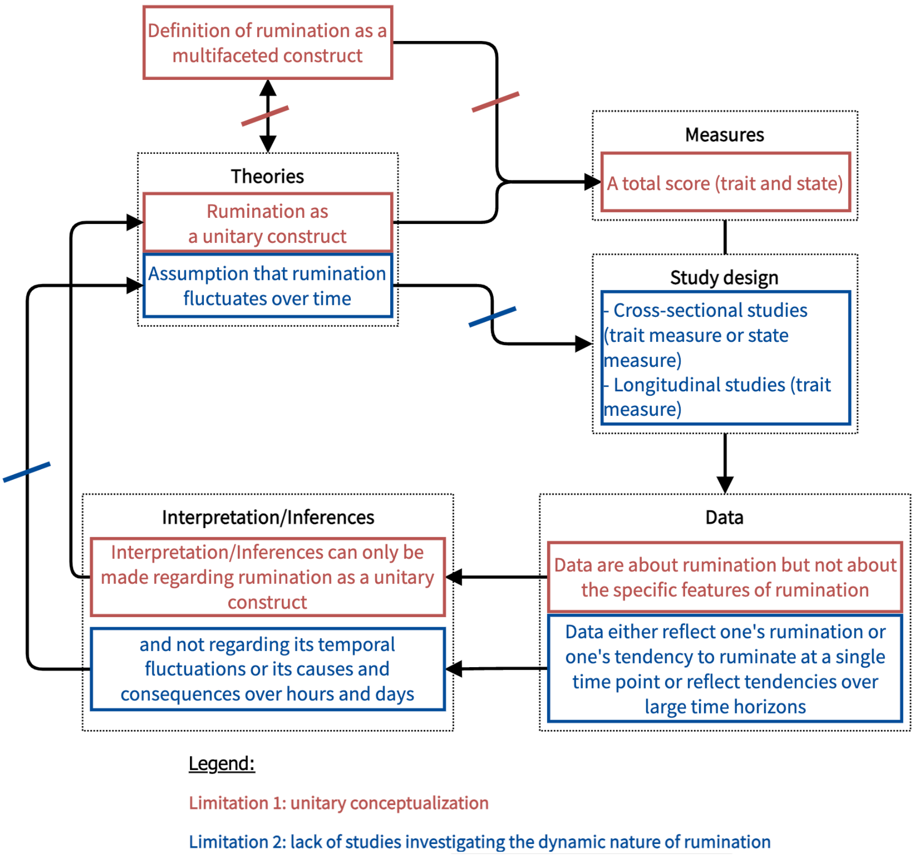
Figure 8. Visual representation of the limitation of inadequate study design to examine the temporal aspects of rumination



Note. Although researchers assume that rumination is a dynamic process, this assumption is not reflected in how rumination is studied. Indeed, cross-sectional studies using trait or state measures of rumination only capture it at a single timepoint, and longitudinal studies with trait measures only capture long-term changes in tendencies to ruminate. Therefore, little is known about the dynamic nature of rumination over hours and days.

3.3 How this thesis addresses these limitations

Figure 9. Visual representation of the two main limitations



Note. The first limitation is that theories mainly conceptualized rumination as a unitary construct by not integrating the different features of rumination. This unitary view can constrain hypotheses and is reflected in rumination measures. Consecutively, the data collected and the inferences about this data only feed the theories in a limited way, given that they do not inform about the role of the different features of rumination. In this way, solely based on this research process, theories do not change as one core assumption (rumination as a unitary construct) is never challenged.
The second limitation is that, even though rumination is considered a dynamic process, the most used study designs do not measure these temporal fluctuations. Consequently, uncertainty remains regarding the temporal fluctuations of rumination over hours and days and how these fluctuations relate to the causes and consequences of rumination. Hence, how rumination is studied, mainly as a static construct, does not provide enough empirical information that could feed into theories; it is in this respect that theoretical development is hindered, as fluctuations of rumination over time, and their causes and consequences, are not directly investigated.

Rumination research has had slow theoretical progress. The previous sections argued that this could be traced back to at least two limitations (see Figure 9 for a visual summary). The first limitation is an incomplete theoretical foundation. It can constrain the scope of hypotheses and, through limited measurement tools, restrict the range of discernible results, leading to findings that cannot inform about the limitations of the theoretical frameworks. More specifically, theories are limited in their conceptualization because they only make hypotheses regarding rumination as a unitary construct, measured through questionnaires with a single total score. This conceptualization completely obfuscates the various characteristics of rumination. The second limitation is the use of inadequate study designs to test the theories. Most research consists of correlational research and rumination measures taken at a single time point or only a few time points. Such research, although useful to describe the associations of rumination with other variables, does not allow to test hypotheses related to the dynamic aspect of rumination, an emotion regulation process that fluctuates over time. In summary, despite the assumed dynamic and multifaceted nature of rumination, rumination is conceptualized and measured in most studies as a unitary construct with either trait questionnaires or state measures of rumination at a single time point.

Addressing these limitations is an important endeavor for future research. It could lead to the development of better measurement tools, and adopting a more varied and robust methodological approach can provide a more comprehensive understanding of rumination. This thesis seeks to address these limitations by combining (a) a multifaceted approach to rumination based on the network theory and (b) an intensive longitudinal research design. Chapter 4 will present the network approach to rumination. It is a conceptualization that takes into account several characteristics of rumination and the fact that these characteristics can interact with each other, causing one another. It also highlights how conceptualizing rumination in this way yields novel insights on its associations with executive control. Chapter 5 will present intensive longitudinal research on rumination. It will illustrate why it is important to study the temporal fluctuations of rumination. This chapter will also highlight how the temporal data can be analyzed using three different analytical frameworks. These two chapters lay the theoretical and empirical foundation necessary to address the two limitations.

All these elements will allow for the collection of new empirical data that is more closely related to a complete conceptualization of rumination, with a more valid measure in connection with its multifaceted aspect. Moreover, based on these empirical results, new hypotheses can be generated that will feed into theories and must be tested in future research. The idea is, therefore, that by using both a multifaceted conceptualization of rumination and more temporal data, new information will emerge that will serve to improve existing theories, and also improve our understanding of the associations between rumination and executive control.

Chapter 4.

Rumination as a network system of interacting components

The previous chapters highlight how research about rumination heavily relies on a unitary conceptualization of rumination, assessed as a trait variable using a sum score. In contrast, according to a recent computational network approach, rumination can be conceptualized as a network system of interacting components (Bernstein et al., 2017, 2019). This approach to studying rumination relies on the network theory of psychology (Borsboom, 2017). Therefore, I will first briefly introduce this network theory, how it differs from a latent variable approach to psychology, and how Bernstein and colleagues used it to reconceptualize and study rumination. The goal will be to use this network approach as the theoretical backbone of my research to conceptualize rumination as a multifaceted concept.

4.1 A primer on the Network Theory of psychopathology

One of the dominant models in psychological research is the disease model: it considers that the various problems people suffer from are 'symptoms' of an underlying 'disorder'. For example, fever and muscle soreness are symptoms of the flu, and the field of medicine can explain the flu and provide medication to treat its symptoms or vaccination to prevent its onset. This model is inspired by Western medicine (Hyland 2011)[1]. Like medical diseases, it is thought that an underlying mental disorder causes psychological symptoms that are often observed together. This disease model of mental disorders has led researchers to investigate and search for the root causes of mental disorders in psychological/environmental/biological variables. However, the disease model of psychology has not fared well. As Borsboom and Cramer (2013, p. 92) put it: "The great unitary schools of thought in psychopathology research that tried to reduce mental disorders to simple psychological, environmental, or biological dysfunctions or predispositions have all tripped over the massively multifactorial etiology of these disorders (Kendler 2005a, Nolen-Hoeksema & Watkins 2011, Zachar & Kendler 2007)." In other words, researchers failed to find a succinct set of variables that allowed them to explain mental disorders

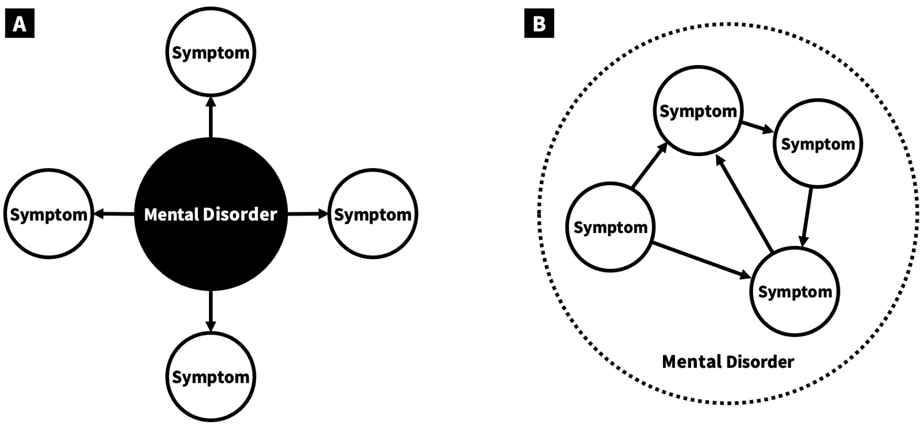
[1] Note that this implied dichotomy of the field of medicine (and the disease model) vs psychiatry is misleading and serves just as an illustration. Indeed, like mental disorders, all medical conditions "can be better and more realistically conceptualized using a network model of signs and symptoms (Zhou et al. 2014)" (Guloksuz et al., 2017, p. 2744). This also paves the way for networks combining medical data and psychological data.

in a reductionist fashion (i.e., breaking things down into smaller/simpler parts to understand the whole) and instead encountered increased complexity.

Psychology needed a way to tackle this complexity. To this end, network theory seemed promising. Indeed, our world consists of complex interconnected systems: neural networks, ecosystems, the internet, the world wide web, the social interactions of a species, consciousness, and many more (Boccaletti et al., 2006). These systems can be conceptualized as networks in which nodes represent the entities (e.g., a web page, a person) and edges/links represent interactions between nodes (e.g., a hyperlink from one web page to another, a friendship between one person and another). Some researchers argued that psychology could benefit from network theory and network analysis to tackle psychology's complexity in the same way that the internet or other systems can be conceptualized as network systems. This led to the formulation of a network approach to psychopathology.

The network approach to psychopathology considers that mental disorders are networks in which the nodes (a circle representing each variable in the network) are the symptoms and the edges (the lines representing associations between variables) are the causal relationships between them (Borsboom, 2017; Borsboom & Cramer, 2013; Cramer et al., 2010). Instead of considering that a mental disorder such as depression (a latent variable) causes various symptoms (see Figure 10a) and is thus responsible for their covariance, the network approach considers that the observed episode of 'disorder' emerges from the network formed by direct relations between the symptoms (see Figure 10b). Hence, the 'disorder' is the label we give to a complex cluster of interacting symptoms, often mutually reinforcing, and causally related through diverse biological, psychological, and societal mechanisms.

Figure 10. Schematic representation of (A) the latent disease model versus (B) the network theory of mental disorders



Note. The latent disease model (A) considers that a mental disorder causes symptoms whereas (B) the network theory of mental disorders considers that a mental disorder is the label given to a set of interacting and causally related symptoms.

For example, instead of considering that a specific substance or construct (that we call depression) causes ruminations, lack of sleep, fatigue, lack of energy and motivation, and negative mood, we could postulate that *lack of sleep* leads to *fatigue*, a *lack of energy and motivation*; people will *ruminate* about their lack of motivation as they are unable to do what they want which will result in a persisting *negative mood*. This illustrates how relationships between symptoms can be conceptualized without needing a common latent cause. In summary, the two basic premises of the network approach to psychopathology are that (a) a single latent psychological or biological entity does not cause the symptoms of a disorder, and (b) psychological symptoms influence one another (Borsboom & Cramer, 2013).

This approach quickly gained allies among researchers and cognitive behavioral therapy clinicians. For instance, many clinicians use functional analysis: this method consists in analyzing and highlighting the functional antecedents and consequences of symptoms and functional relations between symptoms (e.g., compulsions being a consequence of obsessions in some cases). Hence, for clinicians, the network approach can replicate functional analysis by highlighting the causal relations between symptoms (Hofmann et al., 2016; McNally, 2016). It intuitively translates to the study of psychopathology what many have been doing in their clinical practice. For researchers, the theoretical and computational tools of the network approach allow them to study complex associations of multiple variables at once, potentially opening new ways to understand psychopathology and test the functional assumptions made by clinicians. Unsurprisingly, network studies on psychopathology have grown exponentially in the last few years (Blanchard et al., 2023; for reviews, see Contreras et al., 2019; Robinaugh et al., 2019), covering many different disorders: for instance, depression and anxiety (e.g., Beard et al., 2016), bipolar disorder (e.g., Curtiss et al., 2019), post-traumatic stress disorder (PTSD) (e.g., Greene et al., 2020), social anxiety disorder (e.g., Heeren & McNally, 2016).

4.2 Extending the network approach

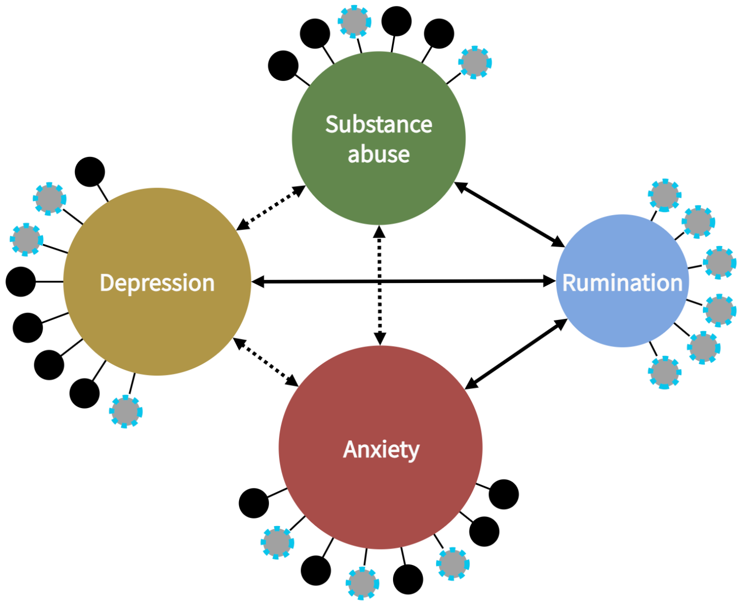
Although the network model of psychopathology of Borsboom and his colleagues solely focused on the causal relationships between symptoms, the same computational tools can be used to study nodes that do not correspond to symptoms. The variables could be transdiagnostic psychological processes or any variable that is thought to play a causal role in psychological disorders (i.e., cognitive, biological, and social variables; Jones et al., 2017). Moreover, if the goal of a network model of psychopathology is to help uncover the 'true' causal associations or suggest plausible causal associations, it must include all relevant variables in the analysis (Epskamp, van Borkulo, et al., 2018). Hence, it is likely that psychiatric symptoms are not the only relevant variables and that other psychological, social, and biological processes should be considered.

Previous studies already included non-symptom variables in network analyses, such as attentional bias for threat (Heeren & McNally, 2016), resilience factors (Hoorelbeke, Marchetti, et al., 2016; Lunansky et al., 2020), genetic risk scores (Isvoranu et al., 2020), and executive functions and rumination (Bernstein et al., 2017). Any variable that can be measured can be included in network analysis as long as it is hypothesized to play a causal role or interact with other variables of the network. This network approach paves the way to study psychological processes that are considered *transdiagnostic*: a transdiagnostic process, such as behavioral avoidance, could connect symptoms from distinct disorders such as social anxiety disorder and obsessive compulsive disorder (Heeren & McNally, 2016). Network analysis could thus help make sense of the comorbidity between disorders by unpacking the associations between symptoms and processes of mental disorders instead of only studying the associations between disorders measured as latent variables.

4.3 The network theory of rumination

Rumination has been increasingly studied over the past years. A good illustration is the growing literature on the associations between rumination and executive control, two psychological processes that are considered transdiagnostic due to their involvement in many different mental disorders. Yet, despite a growing interest and a growing number of published studies, the results regarding the associations between rumination and other constructs, such as executive control, are often mixed, small, and rely mainly on cross-sectional findings and lack causal evidence. Bernstein et al. (2017) hypothesized that these gaps in knowledge between theoretical assumptions and findings could be attributable to how rumination is conceptualized. Indeed, throughout the literature, rumination is conceptualized as a unitary construct and latent variable, measured by a sum score of a self-report measure. Researchers use this single index of rumination to study its relation to other latent variables such as, for example, depression, substance abuse, and anxiety. Figure 11 illustrates this schematically: each latent variable is measured using various items (i.e., the black circles) that are all summed up. The items referring to rumination have a gray background and a blue dotted border. Hence, the figure illustrates how various questionnaires can contain items referring to other constructs (e.g., rumination). This makes sense if the goal is to measure these broad constructs, as anxious people typically have repetitive thoughts, depressed people typically ruminate about the past or their current situation, and people who abuse substances might start doing so because of the need to escape ruminative thoughts.

Figure 11. Rumination and Mental Disorders as Unitary Constructs and latent variables



Note. Each colored circle represents a latent variable and unitary construct measured as a sum score of self-reported items (i.e., the black nodes). The items referring to rumination have a blue border. Hence, this figure illustrates how rumination and other mental disorders are typically studied. Moreover, it illustrates how some items referring to rumination can also be found in questionnaires used to measure mental disorders such as depression, anxiety, and substance abuse.

Hence, one problem is the conceptual puzzle of different measures of mental disorders referring to ruminative thoughts: many measures of mental disorders contain items referring directly or indirectly to ruminative thoughts. Instruments intended to assess distinct constructs have overlapping content and thus are, by definition, not as distinct as initially conceptualized.

Another problem is that, as mental disorders and rumination are studied as broad constructs, results only give descriptive information about the potential causal links between the studied constructs. With these results, we can say two constructs are related, we can differentiate, for example, healthy from clinical populations, but it is impossible to say how or why, for instance, depression and rumination are associated based on the data, which leads to an interpretation of the results beyond what the data allows us to verify.

The last and most striking problem is that, in the same way that depression is not a unitary construct but instead refers to a constellation of heterogenous symptoms (Fried et al., 2014; Fried & Nesse, 2015b), rumination is not a unitary construct either. Although rumination is most often studied as a single index (i.e., a latent unitary construct), most definitions of rumination imply that it is multifaceted, for example, by characterizing the repetitiveness, the valence, and the content of thoughts (e.g., self-focused, focused on the causes and consequences). For instance, according to Nolen-Hoeksema's Response Styles Theory (Nolen-Hoeksema, 1991;

Nolen-Hoeksema et al., 2008), getting stuck in a "self-critical moody pondering", as it has been called, is a driving force underlying the maintenance of rumination. Other research has highlighted the role of passive, judgmental thinking (Raes & Hermans, 2008; Schoofs et al., 2010; Treynor et al., 2003; Watkins & Nolen-Hoeksema, 2014). Moreover, according to Watkins' prominent model of rumination (e.g., Watkins, 2008; Watkins & Teasdale, 2001), repetitive and self-focused processes are key constitutive features of rumination. And indeed, research has shown that those features are strongly related to less adaptive emotional and clinical outcomes (Watkins et al., 2008; Watkins & Moulds, 2005; Watkins & Teasdale, 2001). Hence, several lines of research and conceptualizations have highlighted various aspects of rumination; it is therefore perplexing that rumination is represented as a single index.

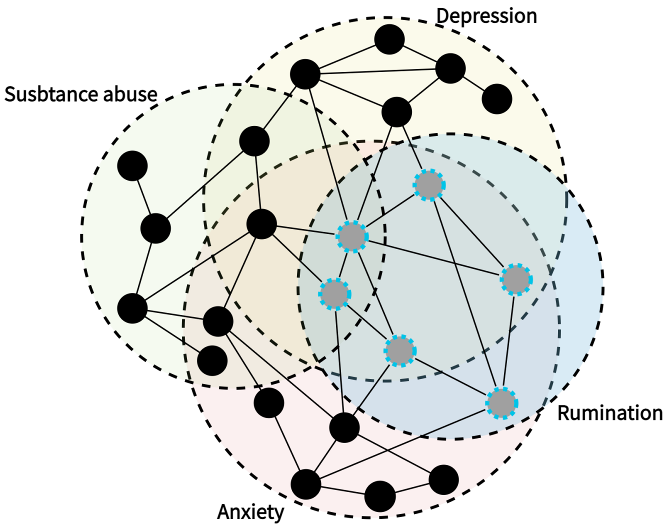
To bridge the gap between rumination's measurement and definition, Bernstein et al. (2017) proposed conceptualizing and studying rumination as a network system of interacting components[2]. Within this network system, each component could be meaningfully linked to other components; the interaction between these components could lead to mutual reinforcements (i.e., feedback loops), which would translate into prolonged rumination. This reconceptualization of rumination has important implications for the way we study it. If rumination can be better conceptualized as a network system of interacting components and if, according to the network theory of psychopathology, mental disorders are made of symptoms such as rumination, then researchers should study the symptoms of mental disorders by distinguishing their various components (if the symptoms can be multifaceted, such as in the case of rumination). In summary, mental disorders are composed of various components (some of which are symptoms), and these components can be further disintegrated into sub-components in some cases.

Figure 12 represents a conceptual network of rumination, depression, anxiety, and substance abuse. The black nodes refer to items measuring specific symptoms of mental disorders and components of rumination, which are all interrelated. These components of depression, substance abuse, anxiety, and rumination are not interchangeable as they share unique associations with other nodes in the network. Moreover, the figure illustrates how different sets of activation of nodes could translate into observing the co-occurrence of, for example, rumination in anxiety and depression. It also makes sense of comorbidity (i.e., between general anxiety and depression) and transdiagnostic processes such as rumination. For example, a person who suffers from major depression and general anxiety could have sleep problems, repetitive thoughts about the past and future, and negative cognitive biases—all symptoms that can be found in people suffering from either depression or general anxiety alone. The same person could also receive the diagnostic of substance abuse disorder if, on top of the previously mentioned symptoms, the person starts to use substances repeatedly to deal with negative emotions, leading potentially to further increases in sleep problems, self-critical and repetitive thoughts, and a further decline in their physical and mental health. Lastly, by looking at the

[2] Note that, as this conceptualization has only been proposed in an empirical paper, its discussion has been limited. I therefore expand the explanation and illustrate the implications beyond what Bernstein et al. (2017) initially discussed.

associations between rumination's components, we might be able to understand rumination better: for example, the fact that one has negative thoughts might make them more difficult to ignore, especially if these thoughts concern the causes and consequences of past events or one's current life situation (e.g., "Why did my father have to leave my mother?", "Why can't I handle stressful situations better?"), which are often unanswerable questions that might make one's thoughts more repetitive.

Figure 12. Rumination and Mental Disorders as Network Systems



Note. Each black node represents a specific symptom or psychological phenomenon. Edges represent hypothetical relationships between nodes. The dotted circles illustrate how a constellation of nodes would be referred to as a mental disorder or as a broad symptom (rumination) if a person were to present these at various (high) intensities.

At this point, it is important to discuss what the exact components of rumination—which this entire section has been alluding to—are. A few have been mentioned, but the past chapters do not contain a definite list of components of rumination. The reason for this is that the exact features of rumination are still up for debate. Indeed, looking at the literature on rumination, it is clear authors ascribe various characteristics to rumination, but it is unclear which properties are most relevant. What makes rumination maladaptive? Is it because the thoughts repeat themselves? Is it because of the negative content of the thoughts? Is it because ruminative thoughts are perceived as uncontrollable?

Although there is no definite answer to these questions (yet), Bernstein et al. (2017) provided initial insights. They investigated the relationship between rumination and executive functions when broken down into distinct components. They recruited 91 participants and measured the three core executive functions (updating, inhibition, shifting) as conceptualized by Miyake et al. (2000) using computerized tasks (an emotional flanker task, an N-back task, and the internal shift task), and they measured five features of rumination based on the Response Styles Theory:

- *Perseveration*: how much participants had been thinking about their performance;
- *Negativity*: how negative their thoughts were;
- *Self-criticism*: how much they had been criticizing themselves;
- *Brooding*: how much they thought about their negative emotional experience;
- *Replaying*: to what extent they replayed parts of what happened in their mind.

The procedure was as follows: participants first completed the computerized tasks, underwent a stressor, then sat alone doing nothing for five minutes, and finally answered the state rumination questions about their thoughts during the five minutes. They analyzed the data using three different types of network analysis: a graphical Gaussian model (GGM) network (i.e., a regularized partial correlation network), a relative importance network, and a directed acyclic graph (DAG). They included a node in these networks for each performance on the three executive functions tasks and each of the features of rumination.

In a GGM network, the edges represent conditional independence relationships between nodes, controlling for the associations between all other nodes (i.e., partial correlations, Epskamp & Fried, 2018). In their GGM, all the components of rumination were strongly interrelated, and criticism was the most connected node (Bernstein et al., 2017). Second, the N-back performance was negatively associated with brooding and flanker performance, whereas other associations between EF tasks and rumination components were small.

The edges in the relative importance network (Heeren & McNally, 2016; McNally et al., 2015) represent the relative contribution the predictor makes to R^2 after controlling for multicollinearity; the arrows represent the direction of the prediction (Grömping, 2007; Johnson & LeBreton, 2004). Based on the results of this network, criticism was again the most connected node from the network; it predicted replaying, brooding, negativity, and perseveration, but it was predicted by N-back performance, perseveration, replaying, and flanker performance. When looking at the thickest edges, two positive feedback loops stand out: (1) brooding strongly predicted flanker performance which in turn predicts criticism which predicted brooding, and (2) negativity strongly predicted N-back performance, which predicted criticism, which predicts negativity. Notably, most pairs of nodes had bidirectional edges between them.

Finally, the DAG represents potential causal relations as it estimates the likelihood of the presence and direction of an edge (Pearl et al., 2016). Such an analysis consists of rendering two networks. In the first network visualization (DAG A), the weight of the edges represents the relative BIC value. The higher the value, the thicker the edge is, indicating the greater importance of this node for the network structure and the more damaging it would be to the model to remove it from the network. The second network visualization uses the directional probabilities to determine the edge's weight (DAG B). In this visualization, a high value and, therefore, a thicker edge indicates a greater probability that this edge points in the depicted direction, reflecting how often that direction appeared in the bootstrapped networks (McNally et al., 2017). Based on the DAG, criticism was again the most influential node, creating a cascade leading to worse performance on the N-back and flanker tasks.

The authors also computed centrality metrics. For instance, the strength metric consists of the sum of the edge weights connecting one node to others. In the case of the relative importance network, this leads to two strength metrics: in-strength, that is, the sum of the weights of connections that are directed to the node, and out-strength, the sum of the weights of connections that originate from the node. Overall, criticism was the most central node in both the GGM and the relative importance network.

Given these results, criticism seems to be the most influential of the five measured features of rumination. It was the most central node in directed and undirected networks (i.e., the node with the most edge weights connected to it) and is also the starting node for the DAG, which is an undirected acyclic graph that allows formulating hypotheses on the direction of causality. Note that conclusions about causality based on these analyses are limited because they rely on cross-sectional data and because the DAG is acyclic, whereas, in psychology, feedback loops are often present.

These limitations set aside, the most striking result is how each rumination component is associated differently with the other components and executive functions. For instance, in the GGM, the strongest connections between rumination components and executive functions consisted of a negative association between the N-back performance and brooding ("How much have you thought about how upset you felt?"), and between the flanker performance and replaying ("To what extent did you replay parts of what happened in your mind?"). Moreover, in the DAG, brooding seems to predict the performance on the N-back task. These preliminary results (as they have not been replicated yet) align with the resource depletion account of the association between rumination and executive control.

Most importantly, Bernstein et al. (2017)'s results showed for the first time that the various components of rumination are not interchangeable. Therefore, a multifaceted conceptualization of rumination as a complex construct is sensible. Moreover, on top of the unique associations with executive functions, the distinct associations between rumination components highlight how, by looking at how the components of rumination interact, researchers might be able to better uncover the mechanisms of rumination. In contrast, a unitary conceptualization would sum all these scores and would be unable to study the distinct contributions of each component in relation to other variables and each other.

Taking this approach one step further, Bernstein et al. (2019) proposed to reconsider trait rumination as a network system. Until then, trait rumination and its subtypes were measured by self-report measures using sum scores. This approach implicitly considered the components of rumination (e.g., items) interchangeable and the product of an underlying latent response style. In contrast to factor analyses and latent variable approaches, the network approach considers rumination as a network of interacting components without specifying an underlying common cause. By using network analysis to analyze cross-sectional responses of healthy participants to the RRS (Treynor et al., 2003), Bernstein et al. (2019) again found that the nodes were not interchangeable as the associations between nodes varied greatly across the network. This concurs with previous evidence (Bernstein et al., 2017) and supports the notion that rumination might be best conceptualized as a multifaceted construct.

In a third study, Bernstein et al. (2020) investigated the effect of aerobic exercise on rumination. Participants were first assigned to thirty-minute cycling ($n = 113$) or stretching ($n = 113$) conditions, followed by a stressful speech task and a resting period. After this resting period, state rumination was measured using the same measure as in Bernstein et al. (2017). They computed four networks (two types of networks * two conditions): two GGM networks and two relative importance networks. They also computed strength centrality for each network. Although the groups did not differ in network structure, the connections between features of rumination in the GGM did differ slightly between conditions. Specifically, there was a weaker connection between self-criticism and other components of rumination for the cycling condition versus the stretching condition. Moreover, echoing these changes in associations, self-criticism was the most central node in both networks for the stretching condition. In contrast, negativity was the most central node in both networks for the cycling condition. In other words, centrality metrics of negativity were higher, and the centrality metrics of self-criticism were lower in the cycling condition compared to the stretching condition.

In summary, it seems that aerobic exercise changed the pattern of associations between the components of rumination. However, the study had an important limitation: it was insufficiently powered to conduct a network comparison test (van Borkulo et al., 2015). Such a test would have allowed for significance testing for any observed differences and, thus, more robust conclusions. Hence, without this information, these results (i.e., the observed differences between networks and the potential impact of aerobic exercise) can only be interpreted as hypotheses to be tested further.

4.4 Summary of the network approach to rumination

The network approach to psychopathology considers that mental disorders can be conceptualized as network systems of causally related symptoms. Bernstein and her colleagues (2017) extended this approach to rumination. Instead of a unitary construct measured by a sum score, they argued that **rumination could be best conceptualized as a network of interacting nodes, with each node referring to a different component of rumination**. According to this view, rumination is a multifaceted construct whose components are causally related (Bernstein et al., 2017). For example, being more self-critical towards oneself might lead to more negative thoughts and brooding, increasing the likelihood of these thoughts becoming repetitive. Hence, rumination is the label given to the observed phenomenon resulting from the interaction of multiple components.

Two studies have explored state rumination as a network system, and another study has done the same for trait rumination. The results suggest that, for both state rumination and trait rumination, the components of rumination are not interchangeable: each component was differently associated with other components of rumination and executive functions. For instance, Bernstein et al. (2017) shed light on the unique associations between the different facets of rumination and executive functions. These results (i.e., the fact that rumination's components are *not* interchangeable) have an important implication: conceptualizing and measuring rumination as a unitary construct obfuscates the complex nature of rumination. Indeed, reducing rumination to a single score might have led researchers to oversimplify rumination as people can obtain equal scores yet differ widely in the underlying features of rumination. In the same way, two people can have the same depressive symptomatology scores yet vary widely in the exact symptoms they are experiencing (Fried & Nesse, 2015b). Hence, although trait rumination reflects a person's overall response tendencies, it might be less useful when the goal is to study the mechanisms of rumination or the effects of an intervention on rumination (Fried et al., 2014; Fried & Nesse, 2015b).

Therefore, this network approach to rumination has at least two benefits. First, it could allow rumination to be better understood by embracing its multifaceted nature and by studying how its components interact. Second, it would allow for a more fine-grained understanding of how the various components of rumination relate to other important psychological, environmental, and biological variables. However, although appealing in terms of basic and translational understanding of rumination, the only three published network studies available so far have measured **rumination as a static construct without considering its potential temporal dynamics per se**. In addition to the limited number of studies, the lack of studies investigating the temporal dynamics of rumination as a multifaceted construct precludes any strong inferences about which features of rumination instigate and maintain rumination when it is conceptualized as a network system.

Chapter 5.

The temporal unfolding of rumination

The previous sections reviewed how rumination could be best conceptualized as a multifaceted construct and a system of interacting nodes, challenging how we think about rumination and how we study rumination in relation to other processes, such as executive control. It addresses the first limitation of the rumination literature, that is, that rumination is measured as a unitary construct despite models considering rumination as a multifaceted construct. However, the network approach to rumination also suffers from the second limitation of the rumination literature: a lack of temporal studies. In this chapter, we will address this limitation and answer important questions: why study rumination temporally? And how?

5.1 Why study rumination temporally?

If one wants to understand why it rains, it makes sense to try to observe the whole process: from how clouds are born, to the first drop of water falling from the sky, to the very moment the blue sky can be seen again. The same logic applies to understanding the storms of thoughts that weather our daily lives. Cross-sectional and prospective research (with timeframes of months and years) are not enough. To really improve our understanding of how rumination works and how it unfolds over time, we need to look at state rumination (i.e., fluctuations in rumination over minutes, hours, and days).

On a conceptual level, two core mechanisms that are hypothesized to cause rumination imply a temporal nature. According to the Goal-Progress theory (Martin & Tesser, 1996b), rumination is a process triggered by a lack of satisfactory progress towards a goal or a discrepancy between a real situation and one's desired goal(s). The Habit-Goal framework (Watkins & Nolen-Hoeksema, 2014) adds that rumination can also be considered a habit of thinking when it has been repeatedly used and has been the preferred emotion regulation strategy of a person.

On an empirical level, research has shown that there are not only long-term consequences of rumination but also consequences in the shorter term. Rumination may cause sustained physiological arousal after a stressor because it would keep active the stressful representations that caused the physiological response in the first place (Brosschot et al., 2006). For instance, state rumination about an arithmetic task was associated with a slower blood recovery from the increase in blood pressure (due to stress) induced by the task (Radstaak et al., 2011). Another study found that high state rumination after a stressor predicted an increased and sustained cortisol response (Zoccola et al., 2008). Finally, a meta-analysis of 60 studies investigating the physiological effects of repetitive cognition like rumination and worrying found that they led to significantly higher blood pressure, higher heart rate, higher cortisol, and lower heart rate variability (i.e., reduced heart rate variability is indicative of suboptimal autonomic nervous system functioning and is associated with poorer health outcomes) (Ottaviani et al., 2016). These findings support the idea that rumination can amplify and prolong physiological and emotional responses.

Anyone who has ever ruminated could reflect and realize that their rumination episodes last anywhere from a few seconds to hours or sometimes even spread over several days. Moreover, they might notice their thoughts fluctuate within a day, weeks, or months, depending on the context and life experiences. Moreover, as rumination is considered an emotion regulation strategy, its use will typically follow the ebbs and flows of our emotional lives. Hence, rumination is not a static construct but instead a process that fluctuates over time. Consecutively, a lack of temporal data withholds researchers from reaching a better understanding of how rumination (i.e., state rumination) directly affects a wide range of emotional, cognitive, and physiological outcomes.

As implied at the beginning of this section, studying rumination as a static unitary construct is akin to studying the weather with once-a-month weather reports that average the weather across the month (e.g., “It has rained on average 72 minutes per day this month”). Worse, imagine the report would rely on surveying people monthly regarding the weather for the past month. With such a report and no possibility of getting further detailed data, noticing trends and patterns would be much more difficult! And it would obfuscate the complex dynamic nature of the weather.

Moreover, studying psychological constructs over hours and days is not new. Already in the early 1980s, the *experience sampling method* (ESM, also called ecological momentary assessment) was introduced (Csikszentmihalyi & Larson, 1987). It consists of repeatedly measuring various variables in the context of people’s daily life (Hektner et al., 2007; Palmier-Claus et al., 2019). For example, researchers would give diaries to participants, with daily questionnaires to fill in. However, technology has made conducting ESM studies much easier: nowadays, researchers can ask participants to answer questions or complete tasks several times a day directly from their phones.

The ESM method can mitigate several methodological issues. For instance, as the gap between the assessed period and the assessment is either reduced (e.g., “How did you feel in the last four hours?”) or absent (e.g., “How do you feel now?”), recall bias is much reduced when using self-report measures (Margraf et al., 1987; Reichert et al., 2020; H. T. Reis, 2012). Indeed, people are more likely to accurately remember emotions and cognitions at hourly/daily timeframes, whereas longer timeframes (e.g., weeks or months) are subject to biased or faulty recall (Shiffman, 2007, 2009). And thanks to the advent of technology (smartphones, smartwatches, automatic measuring devices), conducting ESM studies has become easier than ever. Therefore, the next section provides an overview of how rumination has been studied temporally (in relatively short timescales, i.e., within hours and days, not weeks or months) and what it teaches us about rumination’s mechanisms.

5.2 How to study rumination temporally?

An exhaustive review of the studies investigating temporal associations of rumination is beyond the scope of this chapter. Indeed, ESM studies have investigated rumination in relation to a wide range of clinically relevant variables such as sleep (e.g., Sladek et al., 2020; Takano et al., 2014), work (e.g., Melo et al., 2021; Wach et al., 2021), hallucinations (e.g., Hartley et al., 2014; Jongeneel et al., 2020), and various emotion regulation strategies (Brans et al., 2013). Reviewing such a broad literature and its theoretical implications would almost be worth a whole PhD thesis in itself[1].

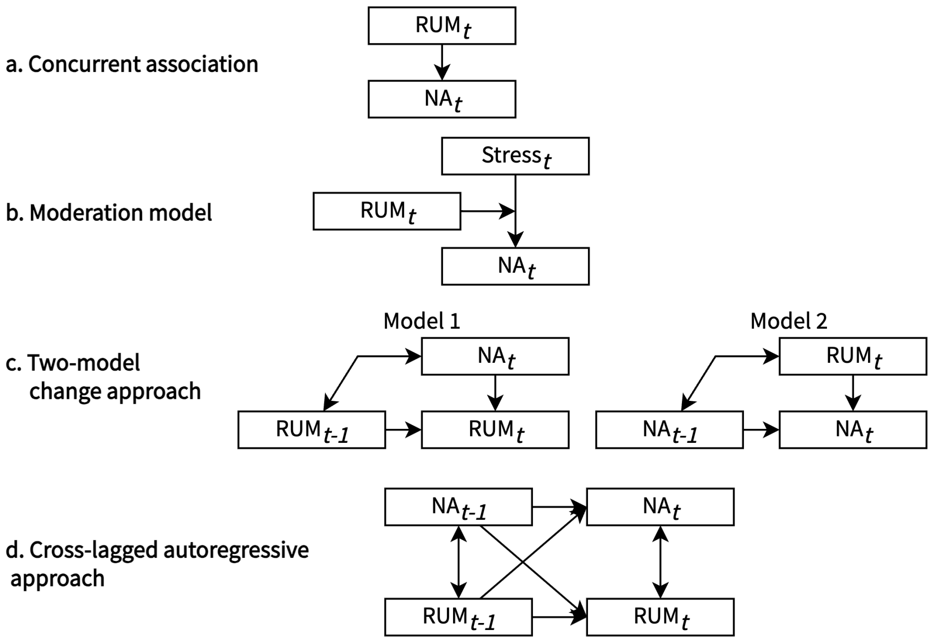
One of the densest bodies of literature on the temporal dynamics of rumination consists of ESM studies that investigated the association between rumination and negative affect (NA). This research is especially interesting considering that rumination has been conceptualized as an emotion regulation strategy used in reaction to NA; rumination is considered an outcome of NA, but it is also thought that rumination exacerbates NA (Calvete et al., 2015; Nolen-Hoeksema et al., 2008). Moreover, NA can be viewed as a proxy for goal discrepancies. Indeed, based on self-regulation theories, negative affect arises as a consequence of a lack of progress towards a goal (Carver & Scheier, 1990). Therefore, results linking NA with state rumination can also be considered indirect evidence of the Goal-Progress theory (Martin & Tesser, 1996b).

Blanke et al. (2021) provide a great overview of this growing research field. Four main lines of research have been conducted. First, evidence was found for the concurrent positive association between NA and rumination using multilevel modeling (e.g., Lennarz et al., 2019); see Figure 13a. Notably, one study directly tested and provided evidence for the Goal-Progress theory by measuring rumination, negative affect, and goal progress in everyday life using ESM: momentary rumination fluctuated concurrently as a function of the goal discrepancies experienced by participants in their everyday lives (Moberly & Watkins, 2010). Interestingly, negative affect mediated the association between goal discrepancies and momentary rumination, but this analysis cannot be interpreted as causation as they rely on concurrent associations, not lagged associations. Second, again using multilevel modeling, rumination was found to moderate the association between stress and NA: rumination increased the detrimental effect of stressors, thereby increasing the NA induced by these stressors (Brose et al., 2011; Genet & Siemer, 2012), see Figure 13b. Third, a two-model approach allowed to find support for a bi-directional relationship between rumination and NA (e.g., Brans et al., 2013): rumination at the previous time point and NA at the current time point predicted rumination at the current time point, and vice versa (see Figure 13c). Results also supported lagged effects: rumination predicted increases in NA at the next time point (Watkins et al., 2008). Although the two-model approach can analyze concurrent associations, inertia (i.e., previous levels of a variable predicting the current levels, interpreted as resistance to change), and lagged associations of rumination and NA at once, it models them in isolation by splitting the process into two univariate processes.

[1] I initially had started a systematic review of intensive longitudinal studies on rumination but abandoned the idea to include it in this thesis. Indeed, after scanning 1508 abstracts, 361 studies were selected for full-text verification; and after checking the full-texts of 218 out of the 361, 151 papers were already selected for the systematic review.

Moreover, as Blanke et al. (2021, p. 9) emphasized, "within the two-level approach it is not possible to evaluate associations between cross-lagged and/or lagged effects. For example, this prohibits exploring whether levels of inertia in negative affect are related to levels of inertia in rumination, which is interesting from a theoretical perspective". A fourth approach to studying temporal associations of rumination allows to account for all concurrent, lagged, and cross-lagged associations (see Figure 13d): it consists in using multivariate vector autoregressive modeling (mlVAR). The mlVAR model captures both the associations within individuals and the differences between individuals, allowing to study multivariate within and between associations (Bringmann et al., 2013).

Figure 13. Schematic illustration of different theoretical model types underlying investigations of the associations between rumination (RUM), negative affect (NA), and stress (Stress)



Note. This figure illustrates the different statistical models used to study the associations between affect, rumination, and stress up until now. Lower *t* represents the current time point whereas *t-1* represents the time point.

The following sections will review ESM/EMA/diary studies about rumination, separated into three main (overlapping) categories: (1) research that analyzed affective and ruminative inertia (based on the field of affective dynamics); (2) research that used temporal network analysis (based on the network approach to psychopathology); (3) ESM research that investigated rumination and negative affect entropy. In doing so, these sections will give an overview of the latest developments in the analysis of temporal data and how these have been used to further our understanding of rumination.

1. *Affective dynamics*

Ruminative inertia in isolation and its association with negative affect inertia

The previous section gave a brief overview of how rumination had been studied in relation to NA and the various methods of analysis used. It illustrated how rumination seems to have a bi-directional relationship with NA: rumination predicting NA at a concurrent and subsequent time point and being predicted by NA at a concurrent and previous time point. Going one step further, one might wonder whether rumination and NA predict themselves at subsequent time points. Such temporal associations of NA have been widely studied, especially in the context of so-called *affective dynamics*.

Affective dynamics research consists of studying the patterns of affective fluctuations and the mean levels of affect over time (Cunningham et al., 2013; Hollenstein et al., 2013; Trull et al., 2015). One of the key metrics used to describe affective dynamics is autocorrelation, also known as *inertia*. Inertia refers to the propensity of a state to carry over from one moment to the next (Kuppens, Allen, et al., 2010). In the last two decades, this metric has mainly been used in psychology to study the temporal dynamics of affect, as well as how affective inertia is associated with and predictive of mental health outcomes such as depression (Houben et al., 2015). Moreover, emotional inertia (of positive and negative affect) has previously been associated with rumination and depression (Brose et al., 2015; Koval et al., 2012), but ruminative inertia had not been studied directly yet. However, considering rumination's repetitive and habit-like nature, it makes sense to study ruminative inertia: that is, how rumination at one time point predicts itself at the next time point.

Researchers only very recently began to investigate ruminative inertia. Some studies have investigated **ruminative inertia at the daily level**. For instance, in a clinical sample composed of patients with current or past depression, Bean et al. (2020) assessed daily rumination for three weeks, as well as current trait depressive symptomatology, the number of total depressive episodes, and their total duration in months before the start of the daily assessments. Rumination carried over from one day to the next and thus showed inertia. Depressive symptomatology was positively associated with ruminative inertia: the higher the depressive symptomatology, the higher the ruminative inertia. However, the association was strongest for high depression scores (1 SD above the mean: $\beta_{1j} = 0.437$, $p < .001$), and the association between ruminative inertia and depression was also significant at lower levels (1 SD below the mean: $\beta_{1j} = 0.129$, $p < .05$). These results are in line with theoretical assumptions and findings. Indeed, as rumination is associated with the onset and maintenance of depressive symptoms, it makes sense that high levels of ruminative inertia—which can be viewed as resistance to change—are associated with depressive symptomatology; perpetual high levels of rumination might be one of the reasons depression is maintained (Bean et al., 2020).

Bean et al. (2021) replicated these findings in a non-clinical sample by assessing rumination daily for two weeks in a sample of undergraduates. Trait depressive symptomatology at baseline was associated with greater daily rumination and greater ruminative inertia. More specifically, daily rumination was more self-predicted by previous-day rumination in participants with higher trait depression (rumination inertia for participants with depression one SD above the mean of depression scores: β_{1j} = .392, z = 11.19, p < .001, 95% CI [.324, .461]) compared to low depression (rumination inertia for participants with depression one SD below the mean of depression scores: β_{1j} = .006, z = 2.58, p = .01, 95% CI [.002, .011]). In conclusion, Bean et al. (2021) found similar findings in a non-clinical sample to Bean et al. (2020) in a depressive sample. The fact that ruminative inertia was higher in people with high depressive symptomatology in both clinical and non-clinical samples highlights the importance of studying ruminative inertia in a broader context.

Another study investigated ruminative inertia by measuring rumination **several times a day**. To investigate the reciprocal effects between negative affect (NA) and rumination, Blanke et al. (2021) used mlVAR implemented by dynamic structural equation modeling in Mplus (DSEM; Asparouhov et al., 2018). This analysis method can model both the within-person associations and the autoregressive nature (inertia) of both rumination and NA within one model.

Using this method with two independent samples of ESM data (ten assessments per day for seven days; and six assessments per day for nine days), Blanke et al. (2021) found that the association between rumination and NA was reciprocal (predicting each other at the next timepoint) when measured on a timeframe of hours. Both processes also showed inertia (predicting themselves at the next time point). In the case of rumination, higher mean levels of momentary rumination were associated with higher ruminative inertia, suggesting that when people have a high tendency to ruminate, they also do it over extended periods.

In a sample of university students, Hjartarson et al. (2021) assessed affect and rumination ten times a day for six days. Using the same analysis method as Blanke et al. (2021), they found inertia effects for NA, rumination, and positive affect (PA). Moreover, the cross-lagged effects of NA and PA on rumination were also significant: higher NA levels predicted higher subsequent rumination, and lower PA levels predicted higher subsequent rumination. Surprisingly, in contrast to Blanke et al. (2021), they did not find that rumination increased subsequent NA, nor did it decrease PA. In a subsequent study, they also investigated how affect and rumination fluctuated over time by assessing variables ten times a day for six days, but in a sample of formerly depressed people (FD) and non-clinical controls (NC) (Hjartarson et al., 2022a). They also took baseline measures of trait rumination, early life stress, and habitual characteristics of negative thinking (e.g., automaticity, lack of conscious awareness, intent, and control). They found that only in the FD group did NA predict subsequent rumination, and did rumination predict subsequent NA. Interestingly, however, both groups showed significant NA inertia and ruminative inertia. Whereas both groups had similar levels of ruminative inertia, the group with a depression history had significantly higher NA inertia than the control group. Hence, these results are in line with previous findings (Blanke et al., 2021; Hjartarson et al., 2021), although cross-lagged effects of rumination and negative affect were only significant in the depressive group, suggesting that rumination in reaction to negative mood is mainly present in depressive people.

However, another study by Rzeszutek & Gruszczyńska (2021) did not replicate these results. By assessing rumination and NA daily in the evening during five days in a sample of people living with HIV, they found that NA's inertia was non-significant—although the authors note that the variance of this parameter was substantial. Ruminative inertia was significant: rumination the previous day predicted increased rumination on the current day. Both cross-lagged effects of rumination at the previous timepoint on NA and NA at the previous timepoint on rumination were non-significant. Moreover, the mean levels of rumination and NA were not associated with cross-lagged effects. These results are inconsistent with the authors' hypotheses and Blanke et al. (2021) findings.

Importantly, several differences among these studies might explain the discrepancies in the results. First, Rzeszutek & Gruszczyńska (2021) asked participants to think of a hassle that happened during the day when answering the daily question of negative affect and rumination; that is, contrary to previous studies, participants had to think of a specific hassle when answering the questions and not answer regarding how they felt or behave during the whole day. Second, they did not remunerate participants, so participants might have responded more carelessly. Third and most notably, the daily measurement and shorter time period (only five days) might have limited the ability of the questions to capture relevant variations in answers, in contrast to the previously mentioned ESM studies (ten times per day for seven days and six times per day for nine days, Blanke et al., 2021; ten times a day for six days, Hjartarson et al., 2021, ten times a day for six days, 2022a) or the other studies with daily assessments (Bean et al., 2020, 2021).

Altogether these results suggest that once initiated, rumination tends to persist (i.e., high inertia) across hours and days, and so does negative affect (see Table 6 for a summary). Moreover, these studies also support the bi-directional association between negative affect and rumination although not all studies replicated it. Lastly, evidence from daily and multiple-times-a-day ESM studies suggests that ruminative inertia might be stronger as a function of depressive symptoms, but the direction of this association is still unclear.

Table 6. Summary of affective dynamics research on rumination

Authors & Year	Sample Description	Methodology	Main Findings	Additional Notes
Bean et al. (2020)	Patients with current or past depression	Daily rumination assessment for three weeks	Rumination shows daily inertia; more pronounced in those with higher depressive symptomatology	Introduced the concept of ruminative inertia; links with depression
Bean et al. (2021)	Undergraduates	Daily rumination assessment for two weeks	Similar to 2020 findings; higher trait depression linked to greater ruminative inertia and higher person-level daily rumination	Extended findings of ruminative inertia to a non-clinical sample
Blanke et al. (2021)	Two independent samples with ESM data	ESM: (1) 10 assessments per day for 7 days; (2) 6 assessments per day for 9 days	Rumination and NA predicted each other from one time point to the next; higher mean levels of momentary rumination were associated with higher ruminative inertia	Demonstrated moment-to-moment ruminative inertia
Hjartarson et al. (2021)	University students	ESM: 10 times a day for six days	Found inertia effects for NA and rumination; PA and NA levels predicted subsequent rumination	Divergence from Blanke et al.: rumination did not increase subsequent NA
Hjartarson et al. (2022a)	Formerly depressed (FD) and non-clinical controls (NC)	ESM assessment 10 times a day for six days, with baseline measures	NA<->rumination link present in FD group only; both groups showed NA and ruminative inertia but the FD group had significantly higher NA inertia	Differentiated the impact of rumination in FD vs. NC groups. Replicated Blanke's et al. findings
Rzeszutek & Gruszczyńska (2021)	People living with HIV	Daily assessment for five days	Ruminative inertia significant, NA inertia non-significant; no link between mean levels and cross-lagged effects	Noted methodological differences that may explain variance from other studies

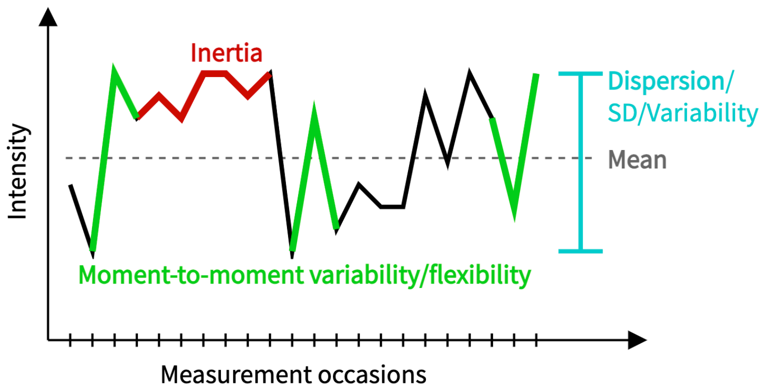
Note. ESM = Experience sampling method; NA = negative affect; PA = positive affect; FD = formerly depressed; NC = clinical controls.

Other metrics used in the context of affective dynamics

The study of affective dynamics relies on the assumption that it is because our emotions fluctuate that they hold meaning and give meaning to our lives (Kuppens, Oravecz, et al., 2010). Thus, better understanding the dynamics of affect through metrics such as inertia might help to complete theories about the associations between affect and mental well-being. Although only inertia has been studied in the context of rumination and affect, many other metrics have been investigated in research about affective dynamics. Two are worth mentioning as they could be applied to rumination: moment-to-moment variability and within-person variability.

The first additional metric is the within-person standard deviation or variance. It is referred to as the 'variability' of a variable. It is also referred to as 'dispersion' by some authors (e.g., Bos et al., 2019) to avoid confusion with the usual concept of variability and standard deviation. The second additional metric is 'instability' or 'moment-to-moment variability'. It consists of the mean square successive difference (MSSD or its square root: RMSSD) (Jahng et al., 2008). It captures both the magnitude and temporal dependency of the dynamics of a variable, in contrast to inertia, which captures only the temporal dependency of a variable from one timepoint to the next, and SD, which captures only the magnitude of fluctuations (Jahng et al., 2008). The results of a meta-analysis on the relationship between psychological well-being and affective dynamics metrics indicate that higher inertia, higher moment-to-moment variability, and higher dispersion, were all associated with lower levels of well-being overall (overall $\hat{\rho} = —.151$, overall $\hat{\rho} = —.205$, and overall $\hat{\rho} = —.178$, respectively). Figure 14 illustrates these metrics.

Figure 14. Illustration of within-person dynamic metrics



Note. Inertia = the propensity of a state to carry over from one moment to the next; Moment-to-moment variability/flexibility = captures the range of moment-to-moment fluctuations in intensity; Dispersion/SD/Variability = captures the magnitude of fluctuations over the whole measurement period.

Note that neither dispersion (within-person standard deviation) nor moment-to-moment variation have been used to study rumination, nor has it been theorized whether and how these metrics could be useful to understand rumination further. Moreover, although the three metrics (dispersion, moment-to-moment variation/flexibility, and inertia) have been used in many studies summarized in the previously mentioned meta-analysis, an important limitation of this literature is that the conclusions about associations between these metrics rely on zero-order correlation (see the meta-analysis by Houben et al., 2015): that is, the results indicating that, for example, instability of affect is associated with worse well-being does not take into account the effect of other variables such as within-person mean levels of affect, affect dispersion, or inertia of affect. This is especially worrying as two studies show that the associations between these dynamics metrics and mental health indicators become non-significant after controlling for other affect dynamic metrics and within-person mean levels of affect. Indeed, Koval et al. (2013) and Bos et al. (2019) found that when adjusting for the other dynamic metrics and mean levels of affect, the associations between dispersion and depression, inertia and depression, and moment-to-moment variability and depression became non-significant. Thus, this research highlights how the current literature on affective dynamics has a big caveat: its results might be rendered void when considering mean levels of affect.

In addition to this, these two studies also discuss a key implication, that is, high moment-to-moment fluctuations might be adaptive instead of maladaptive:

> "Important emotion theories suggest that some degree of moment-to-moment variability in affect may even be healthy and adaptive, because it enables us to adequately respond to environmental demands (Carver, 2015; Frijda & Mesquita, 1994; Kashdan & Rottenberg, 2010; Panksepp, 2012). It is therefore not surprising that in some parts of the literature, 'moment-to-moment variability' is referred to with the term 'flexibility' (e.g., Hollenstein, 2015; Kashdan & Rottenberg, 2010), which has a positive connotation. Fluctuations in affect may especially be functional at the shorter timescale, that is, seconds or minutes. At this timescale, moment-to-moment variability may reflect functional responsiveness to situational contingencies (Koval et al., 2016). At longer timescales (e.g., several hours or days), moment-to-moment variability may rather reflect mood swings and may thus be unfavourable (Koval et al., 2013)." (Bos et al., 2019, p. 822)

2. Temporal network analysis

Autocorrelation, mlVAR, and temporal network analysis

Inertia, most commonly referred to as autocorrelation or autoregressive effects outside of the field of affective dynamics, has also been used in temporal network analysis, which is a type of analysis that can account for autocorrelation and associations between several variables at once. Instead of only studying the association between two variables (rumination and NA), several variables are measured over time and all of their associations are analyzed (with all variables being used as outcomes and predictors). Such analysis relies on using multilevel vector autoregressive modeling (mlVAR). Indeed, due to the multivariate nature of studying the concurrent, autoregressive, and cross-lagged effects of multiple variables, mlVAR modeling is ideal for conceptualizing the interactions between multiple variables over time as a network system (Bringmann et al., 2016; Epskamp, Waldorp, et al., 2018; A. J. Fisher et al., 2017). Depending on the exact type of modeling used (e.g., as implemented in R by Epskamp et al. (2018) or as implemented in Mplus by Asparouhov et al. (2018)[2]), mlVAR modeling can account for contemporaneous (i.e., concurrent) associations, temporal associations (i.e., cross-lagged effects and autoregressive/inertia effects), and between-subjects associations. Then, using, for example, Epskamp et al.'s (2018) methodology, the results can be represented using three networks: a contemporaneous network, a temporal network, and a between-subjects network.

A few studies have used an mlVAR model to study the associations between rumination and other variables. For instance, Pavani et al. (2017) measured five emotion regulation strategies (i.e., rumination, appreciation, positive reappraisal, distraction, and expressive suppression) as well as affective experience (i.e., positive affect, PA, and negative affect, NA) in a non-clinical sample using ESM (specifically, five assessments a day for two weeks). They analyzed this temporal data with a mlVAR, which accounted for lagged associations and autoregressive effects but not concurrent associations. In line with previous research (Blanke et al., 2021), rumination at the previous time point predicted more NA and less PA in the current time point, and NA at the previous time point predicted more rumination in the current timepoint (Pavani et al., 2017). Moreover, rumination and NA had autoregressive effects (i.e., inertia). Temporal associations were also found for the other emotion regulation strategies. For instance, positive reappraisal and appreciation at time *t-1* predicted less negative affect at time *t*, whereas both predicted more PA. Altogether, these results indicate that emotion regulation strategies triggered by a type of affect (negative or positive) will tend to perpetuate the same affective experience.

In a sample of people with auditory verbal hallucinations, Jongeneel et al. (2020) measured several variables ten times a day for six days (rumination, negative affect, positive affect, auditory verbal hallucinations, dissociation, and paranoia). In addition to computing temporal associations as did Pavani et al. (2017), they also computed contemporaneous (within the same timepoint, undirected) and between-subjects (undirected) associations using mlVAR. Jongeneel et al. (2020) found a high partial correlation between intrusions and rumination; therefore, they combined the two variables into one 'uncontrollable thoughts' factor. Like previous studies, all variables showed positive autocorrelation. Interestingly, when accounting for all group-level (between-subjects) or contemporaneous (within the same timepoint) associations, uncontrollable thoughts were not predicted by nor predicted negative or positive affect. However, auditory verbal hallucinations and dissociation predicted subsequent uncontrollable thoughts. On a between-subjects and contemporaneous level, uncontrollable thoughts were positively associated with dissociation, auditory verbal hallucinations, and negative affect but negatively associated with positive affect. These results are somewhat surprising and inconsistent with the previous findings associating negative affect and rumination. However, this might be due to discrepancies in how rumination was measured and the sample's characteristics.

[2] The R version does sequential univariate estimation while MPlus does multivariate estimation all at once, using Bayesian estimation.

Another study used temporal network analysis (i.e., a mlVAR analysis with the resulting contemporaneous, temporal, and between-person networks) to study emotion regulation in children and adolescents (Gadassi Polack et al., 2021). They measured rumination and other emotion regulation strategies each evening for twenty-one days. On a temporal level, self-criticism and problem-solving predicted rumination the next day. Surprisingly, rumination did not predict itself from one day to another. In contrast, other emotion regulation strategies (distraction, dampening, problem-solving, positive rumination) and self-criticism showed autocorrelation. On a contemporaneous level, rumination was positively associated with problem-solving, self-criticism, and distraction. On a between-subjects level, rumination was positively associated with problem-solving, distraction, dampening, and self-criticism.

A previously mentioned study in the executive control training section also used temporal network analysis (Hoorelbeke, Van den Bergh, et al., 2022). In this study, the authors sought to examine the effect of executive control training vs. an active control training condition in remitted depressed patients on emotion regulation strategies. To this end, participants answered questions about emotion regulation and depressive symptoms six times a day for four weeks after initial baseline measurements. The experimental manipulation occurred during weeks two and three. At a temporal level and looking at both conditions, the main finding is that ruminative inertia was found consistently before, during, and after the training. Rumination was also negatively predicted by resilience, and rumination positively predicted and was positively predicted by depressive symptoms. However, these associations were not consistently found in both groups nor before, during, or after training. On a contemporaneous level and considering both conditions, rumination and depression were strongly correlated with each other but negatively correlated with reappraisal and resilience, and reappraisal and resilience were strongly positively correlated. Importantly, there were no significant differences between the networks of the two conditions, indicating that cognitive control training did not influence the temporal or contemporaneous network structures. In summary, the mlVAR results are in line with previous research linking rumination to depressive symptomatology and other emotion regulation strategies, but the theoretical implications of these mlVAR results are limited.

This list of temporal network studies gives a broad overview of how rumination has been studied as a network system using ESM or daily diary studies (see Table 7). Most studies investigated the associations of rumination either in relation to affect or other emotion regulation strategies. In several studies, rumination showed inertia, indicating that people who ruminate then to do so for longer times, in line with the results from studies on ruminative inertia in the previous section, and in line with the Response Styles Theory and the habit-like nature of rumination (Watkins & Nolen-Hoeksema, 2014). In contrast, the link between negative affect and rumination is in line with the 'goal discrepancies' part of the Habit-Goal framework (Watkins & Nolen-Hoeksema, 2014) which postulates that goal discrepancies can trigger rumination. Additionally, in contradiction to the impaired disengagement hypothesis, Hoorelbeke's et al. (2022) results suggest that improving executive control does not necessarily alleviate rumination. Finally, no temporal network study has investigated the resource depletion account.

Table 7. Summary of mlVAR studies on rumination

Authors & Year	Sample Description	Methodology	Main Findings	Additional Notes
Pavani et al. (2017)	Non-clinical sample	ESM: Five assessments a day for two weeks	Previous rumination predicted more NA and less PA; NA predicted more rumination; rumination and NA had inertia.	Showed the importance of rumination and NA autocorrelation in emotion regulation.
Jongeneel et al. (2020)	People with auditory verbal hallucinations	ESM: ten assessments a day for six days	Intrusions and rumination combined into 'uncontrollable thoughts'; dissociation and hallucinations predicted subsequent uncontrollable thoughts.	Found that affect did not predict uncontrollable thoughts when accounting for group-level associations. Inconsistencies compared to previous research might be due to the way they measured rumination and the specific sample type
Gadassi Polack et al. (2021)	Children and adolescents	Evening assessments for twenty-one days, temporal network analysis	Self-criticism and problem-solving predicted next-day rumination; rumination did not predict itself (i.e., no inertia).	Highlighted different emotion regulation strategies and their temporal dynamics in younger populations
Hoorelbeke et al. (2022)	Remitted depressed patients	ESM six times a day for four weeks	Ruminative inertia found; rumination and depressive symptoms predicted each other.	No significant differences in the temporal networks' associations between active control and EC training conditions.

Note. ESM = Experience sampling method; EC = Executive control; NA = negative affect; PA = positive affect.

3. *Information theory & entropy*

In addition to the affective dynamics and temporal network approaches, rumination dynamics can also be elucidated using information theory. Information theory, developed by Claude Shannon in the 1940s, provides a mathematical framework for quantifying information and uncertainty (Shannon, 1949). A key metric derived from information theory is entropy, which measures the unpredictability, uncertainty, or randomness in a set of data.

Specifically, entropy (also known as Shannon entropy) quantifies the information contained in set of data, which could for example be a system's trajectory through different states over time. A system transitioning through many unpredictable states has higher entropy and contains more information. Conversely, low entropy systems follow more predictable patterns. A low entropy time-series is more predictable because the probability distribution of states is skewed towards a few dominant states that occur more frequently. Knowing the current state provides greater certainty about forecasting the next state compared to a high entropy system with a more uniform distribution of states. Importantly, entropy can be applied to study the dynamics of both individual time-series or multiple interacting time-series. Unlike autocorrelation which concerns how well past values in a series predict future values (indicating a pattern or predictability), entropy is concerned with the amount of uncertainty or information inherent in the data (indicating randomness or lack of predictability). Hence, for psychological phenomena like rumination, entropy metrics can provide insight into the complexity and unpredictability of temporal fluctuations.

One type of entropy used in psychology research to date is *visit entropy* (Hollenstein, 2013). Visit entropy measures the extent to which the transition between one state to another is unpredictable. To illustrate visit entropy, let us contrast two systems. A first hypothetical system only has two states (e.g., A and B) and always alternates between these two states (e.g., *ABABAB*). By knowing the current state of this first system, one can predict the next state and the entire sequence. Thus, this system has *low* visit entropy — it is very predictable. A second hypothetical system goes through a series of random states (e.g., *AAVSEL*). In contrast to the system with only two states, the second system would be referred to as a system with *high* visit entropy. This system is unpredictable as the knowledge of one state does not allow to easily predict the trajectory of the following states (Hollenstein, 2013). Moreover, in the context of information theory, one would say that the second system contains more information, reflected in the number of letters required to represent the states of a system: *ABABAB* requires two letters, whereas *AAVSEL* requires five letters.

Building on these concepts, researchers have used entropy to characterize the unpredictability/complexity of rumination and affect time-series data. The following sections examine the only two studies leveraging entropy to study rumination, which looked at the interplay between rumination and negative affect over time.

The entropy of affect and rumination

Koster et al. (2015) aimed to study the entropy between affect and rumination to clarify their relationship. Indeed, one of the core assumptions regarding rumination is that negative mood (i.e., affect) can trigger it and that rumination might, in turn, contribute to maintaining a negative mood (Nolen-Hoeksema, 1991; Nolen-Hoeksema et al., 2008). This might explain why rumination is such an important process involved in the onset and maintenance of depression (Nolen-Hoeksema et al., 2008). In this study, they wanted to investigate whether the interplay between rumination and negative affect is different in healthy controls compared to major depressed patients by using entropy; and, more specifically, whether this rumination/mood interplay is more or less predictable (i.e., differences in entropy) in one group compared to another.

To this end, they assessed state rumination and mood ten times a day for two days in remitted major depressed patients (RMD) and healthy controls (CTL). To measure state rumination, they used two items, one for brooding, and one for reflection. They also measured depression and trait rumination at T1 and at T2 six months later. And they computed joint visit entropy as a combination of all the possible states a person could be in, considering their rumination and affect. Low visit entropy would mean that the interplay between rumination and affect is easily predictable as they are only in a few possible states, whereas high visit entropy would mean that their interplay is highly complex and unpredictable.

Their results indicated that, although RMD had higher average state rumination and more negative mood than CTL, the visit entropy between groups was not significantly different. However, they also investigated whether visit entropy, compared to trait depression and trait rumination at T1, predicted trait depression and trait rumination at T2 six months later. In both the RMD and CTL groups, depression scores at T1 predicted depression scores at T2. Moreover, controlling for T1 depression, visit entropy predicted depression scores at T2 (explaining 16% additional variance) for the RMD group but not CTL. Regarding rumination, brooding at T1 predicted brooding at T2 in both groups. When accounting for visit entropy, the change in variance tended towards significance[3] in both the RMD group (i.e., 5%, p = .098) and the CTL group (i.e., 7%, Koster et al. p = .075). In summary, (a) the groups did not differ in levels of rumination-mood visit entropy, (b) controlling for baseline symptoms, visit entropy contributed to predicting future depressive symptoms in the RMD group but not in the CTL group, (c) and entropy contributes marginally to predicting future brooding in both groups.

These results support the idea that higher entropy levels are associated with maladaptive outcomes (as illustrated by the results for depressive symptoms and trait brooding) and have added utility compared to mean levels of momentary symptoms (which, in contrast to entropy, did not explain additional variance). Nonetheless, there were a few limitations. The small sample size and the short duration of the study (i.e., only two days) might have limited the ability to assess entropy correctly; the variability in responses might be larger in longer assessments, for example. Moreover, Koster et al. (2015) assessed rumination with only two items (from Watkins et al., 2008) summed together. Lastly, although the study used ESM data, the metrics used do not provide any insights into the potential causal associations between mood and rumination; visit entropy is a purely descriptive measure.

Fang et al. (2019) conducted a similar study to replicate and extend the previous findings about entropy in a sample of undergraduate students. Using ESM, they asked participants to report state rumination and affect eight times a day for seven days. Trait rumination and trait depressive symptomatology were assessed at the beginning of the study and six weeks later.

Overall, the results are consistent with the previous study. First, using zero-order correlations, they found that higher state rumination was significantly correlated with lower affect (r = –0.31, p = .015), while visit entropy was significantly correlated with higher state rumination (r = 0.68, p < .001), and lower affect (r = –0.28, p < .05). Second, they found that visit entropy predicted trait rumination at follow-up even after controlling for baseline rumination and depression (visit entropy explained an additional 4% (p < .05) variance). Similarly, when also accounting for mean levels of state rumination and affect, visit entropy only significantly predicted trait rumination at follow-up (accounting for 5% additional variance (p < .05)) but not depression at follow-up.

[3] The authors report the results in this way.

Koster et al. (2015) and Fang et al. (2019)'s findings suggest that entropy, in addition to trait measures, can be considered a useful predictor for rumination. In contrast, mean levels of state rumination and affect were not predictive of future rumination. This highlights the potential of using information theoretic metrics such as entropy to investigate the interplay between state variables and their impact on mental health.

There were some notable limitations to these studies. The ESM measures may not have adequately captured within-person fluctuations. Fang et al. (2019) reported high intra-class correlation (ICC) values for the rumination (ICC = 0.88) and affect (ICC = 0.96) items. The ICC represents the proportion of total variance attributed to between-person differences (Snijders & Bosker, 1999). Values near 1 indicate little within-person variance. For ESM research, ICCs below 0.5 are optimal and 0.2-0.4 are common (Bolger & Laurenceau, 2013). The high ICCs suggest the ESM items were not sensitive to changes within individuals over time, instead reflecting stable between-person characteristics. Capturing substantial within-person variance is critical for studying momentary processes like state rumination. These high ICC values indicate that the ESM items did not capture within-person dynamics in rumination and affect. Therefore, the high ICC values for the ESM rumination and affect measures may have limited the conclusions of this study. ESM measures with greater within-person sensitivity could reveal different patterns.

The use of entropy also has some key limitations in these studies. First, entropy is a purely a descriptive measure unpredictability/complexity that does not provide insight into causality. Second, the specific approach used to compute bivariate entropy between rumination and affect, based on Hollenstein's (2013) method, precludes examining multivariate entropy across more processes. Third and most critically, the meaning of entropy levels remains unclear. While higher affect-rumination entropy appears associated with worse mental health outcomes, the reasons are unknown. Koster et al. (2015) argued that higher entropy levels (that is, higher unpredictability) could mean that participants ruminate even when in a neutral or positive mood. High entropy could reveal that rumination has become context-independent and perhaps has become a habitual type of thinking (Watkins & Nolen-Hoeksema, 2014), which could explain why people would ruminate even when in neutral or positive mood. Overall, like the role of flexibility/variability in mental disorders, the adaptive/maladaptive role and meaning of higher visit entropy remains an open theoretical question.

Future studies could use other information theoretic metrics that address these limitations. One such candidate is transfer entropy, which is an information theory metric that quantifies the amount of directed information flow between two random processes (Schreiber, 2000) or several random processes in its multivariate extension (i.e., multivariate transfer entropy, Novelli & Lizier, 2021). Transfer entropy quantifies the degree of uncertainty reduced in the future value of Y by knowing the past states of X, given the past values of Y. In contrast to the entropy metric used in Koster et al. (2015) and in Fang et al. (2019), transfer entropy has been used with multivariate datasets, is a measure of causal dependency[4], and can be more easily interpreted than entropy. And, in contrast to multilevel vector autoregressive models, transfer entropy captures both linear and non-linear effects and is not limited to investigating the associations at one specific lag but can instead capture dependencies between variables at several different lags. Transfer entropy has shown utility in fields like neuroscience for studying networks (Wibral, Vicente, et al., 2014) but has not yet been applied in psychology research.

Given the advantages of this statistic (i.e., multivariate, considering several lagged dependencies, capturing both linear and non-linear effects), future research could harness multivariate transfer entropy to elucidate open questions regarding the dynamics of rumination and, for instance, executive control. This measure holds promise for quantifying the complex temporal interplay between psychological processes by capturing non-linear effects across time lags in a multivariate system.

5.3 ESM rumination measures

The way rumination is measured in intensive longitudinal studies so far is problematic for three reasons: a unitary view of rumination, high heterogeneity among items, and a lack of validation.

A key limitation of the current rumination research discussed in the first two chapters was the fact that rumination is conceptualized and measured as a unitary construct. Limitations of such a unitary view can also be exemplified by ESM research presented in this section (see Table 8). For instance, one of the most common ways to measure rumination in ESM research relies on two items, which are summed up to create a total score, and were first used by Moberly and Watkins (2008). Participants were asked, "Since the previous signal, to what extent were you…", with two items for rumination, "Focused on feelings" and "Focused on problems". These same items were used in several other studies mentioned earlier (Fang et al., 2019; Hoorelbeke et al., 2019; Hoorelbeke, Koster, et al., 2016; Hoorelbeke, Van den Bergh, et al., 2022; Koster et al., 2015). In other studies, researchers either adapted items from existing measures or created new items (Brose et al., 2015). Several studies only used one item (Blanke et al., 2021; Jongeneel et al., 2020; Pavani et al., 2017). In contrast, some daily-diary studies used items from the Ruminative Response Scale (RRS; Treynor et al., 2003; Bean et al., 2020, 2021; Rzeszutek & Gruszczyńska, 2021) or used an abbreviated form of the Momentary Ruminative Self-Focus Inventory (Connolly & Alloy, 2017; Hjartarson et al., 2021, 2022a). Hence, all intensive longitudinal studies studied rumination as a unitary construct without looking at individual features of rumination.

[4] Here the term causality refers to the notion of Granger causality: a variable X is said to granger-cause a variable Y if knowing the past states of X improves the prediction of Y (Granger, 1969).

Table 8. Examples of ESM rumination items

Studies	Frequency	ESM items
Fang et al. (2019); Hoorelbeke et al. (2016, 2019); Hoorelbeke, Van den Bergh, et al. (2022); Koster et al. (2015); Moberly & Watkins (2008).	Several times a day	“Since the previous signal, to what extent were you focused on feelings" “Since the previous signal, to what extent were you focused on problems"
Brose et al. (2015)	Several times a day	“Today, I keep thinking about something again and again” “Today, I cannot get certain things out of my mind” “Today, I have difficulties suppressing thoughts about myself”
Pavani et al. (2017)	Several times a day	“I have wasted time thinking of a past event again and again”
Jongeneel et al. (2020)	Several times a day	“My thoughts won’t let go”
Blanke et al. (2021)	Several times a day	“Since the last beep, have you brooded about something in the past?”
Gadassi Polack et al. (2021)	Daily	“I thought: ‘I’m ruining everything’” “I thought: ‘I am disappointing my friends, family, or teachers’ ”.
Bean et al. (2020, 2021)	Daily	15 items from the RRS
Rzeszutek & Gruszczyńska (2021)	Daily	2 items from the RRS (rephrased to refer to “today”): “I’ve been thinking about what I’ve been doing to deserve this” and “I’ve been wondering why I have problems that other people don’t have”
Hjartarson et al. (2021, 2022)	Daily	(a) Right now, I am thinking about how happy or sad I feel. (b) Right now, I wonder why I react the way I do. (c) Right now, I am thinking about the possible meaning of the way I feel.

Note. RRS = Ruminative Response Scale (Treynor et al., 2003).

A second limitation is the high heterogeneity in the phrasing of the rumination items. In contrast to trait self-report scales that contain many items intended to measure several related aspects of the same construct, ESM items are typically short and few. The limited number of ESM items included in ESM studies means choosing the right items is even more crucial as different items might lead to different results, and the brevity of ESM items means each word carries weight. Word choice likely impacts what aspect of rumination is captured. For example, “focused on feelings” and “focused on problems” imply measuring two different types of thoughts but this distinction might not be straightforward: these items rely on the implicit assumption that participants can distinguish these two thought processes and answering these questions might be complicated as problems often lead to an emotional reaction and might therefore be inseparable. Another example is the difference between “I cannot get certain things out of my mind”, which suggests intrusive/uncontrollable thoughts, while “thinking again and again" implies repetitive thought. Given the ESM items used in rumination research vary greatly yet always refer to 'rumination', it is difficult to generalize or compare their results.

A third related limitation is that the reliability and validity for most ESM rumination items was not established. Without psychometric evaluation, it is unclear if items consistently measure the same construct or relate to rumination as expected. Moreover, if researchers want to investigate the temporal fluctuations of psychological variables, ESM measures need to be able to capture sufficient within-person variability. Yet existing studies either do not verify whether their items captured sufficient within-person variability compared to between-person variability, or report high intra-class correlations (Snijders & Bosker, 1999). Both cases are problematic, for the former, because a basic assumption of ESM research is not verified, and for the latter, because the high ICC indicate that their measures failed to capture within-person fluctuations, which often they aimed to study (e.g., Fang et al., 2019). Such a high ICC can indicate either that the items are not sensitive enough to capture within-person variance or that the ESM study design is suboptimal (e.g., time between assessments or duration of the ESM study).

Hence, ESM studies about rumination relied on a unitary conceptualization of rumination, measured by different items put under the same umbrella term 'rumination', with either unverified or bad psychometric properties. Future research should therefore develop and validate ESM rumination measures. Ideally, these measures should assess rumination as a multifaceted construct, tapping unto distinct rumination facets with multiple complementary items. In this process, it will be important to also optimize the frequency and timing of assessments to capture within-person rumination dynamics while minimizing participant burden.

5.4 Summary and conclusion

This chapter reviewed intensive longitudinal research on rumination to understand how rumination's dynamics have been studied, highlight promising analysis methods, and identify limitations. Three recent approaches were covered.

First, the affective dynamics approach suggests that not just how we feel on average but also the variability of our emotional experiences impacts our mental health. In extending this approach to rumination, studies found that NA and rumination predicted each other, that rumination showed inertia, and that higher ruminative inertia was associated with worse depressive symptomatology. This ruminative inertia — how much a person ruminates at one moment predicting how much they ruminate at the next moment — potentially reflects the habitual nature of rumination. These findings support the Response Styles Theory and also, albeit indirectly, the Goal-Progress theory (as NA can be considered a proxy of goal discrepancies). However, the predictive value of metrics such as inertia still need to be examined further.

Second, temporal network analysis extends the network theory of psychopathology to time-series data. This method of analysis captures the dynamic interplay among multiple factors concurrently, revealing the temporal, contemporaneous, and between-subjects associations, and thereby revealing potential causal pathways. Using this method, researchers uncovered complex multivariate associations between rumination and several other variables fluctuating over time. Most findings highlighted the maladaptive nature of rumination and its associations with negative and positive affect, but theoretical implications for rumination were not always clear.

Finally, entropy, a measure based on Information Theory, quantifies the joint behavior of two variables — in contrast to statistics such as the mean which characterize variables in isolation. The entropy of rumination and affect represents how unpredictable their interplay is, and findings suggest that higher entropy was associated with worse mental health. However, because this measure of entropy does not account for causality, the interpretation of these results is still tentative. Therefore, other information theoretic metrics such as transfer entropy might be more useful to study rumination as a multifaceted dynamic process.

Amid these insights, a critical limitation surfaces: the measurement of rumination. In all these studies, rumination is assessed as unitary construct without looking at its specific features, potentially limiting the depth of our understanding, which echoes the limitations highlighted in Chapter 3. This is especially problematic as the diversity of ESM items used to measure rumination calls into question the generalizability of these results. Additionally, the majority of studies relied on measures and ESM study designs without established validity or psychometric properties or did not assess the psychometric properties of their ESM items.

In conclusion, while the reviewed research supports the theoretical foundation laid by the Response Styles and Goal-Progress theories, this literature and its limitations leaves several questions unanswered—particularly regarding the measurement of rumination, its multifaceted nature, and the role of executive control. The need for a more refined and validated approach to measuring rumination is clear; a methodology that captures its multifaceted nature could unravel the nuances of its mechanisms, foster a more granular understanding of rumination's role in mental health, and inform the development of targeted interventions.

Chapter 6.

Thesis objectives

Two primary limitations characterize current research on rumination. First, the predominant use of a unitary view in conceptualizing and measuring rumination overlooks its complex, multifaceted nature. Second, research often treats rumination as a static construct, focusing on general tendencies or state measurements at a single time point, rather than its fluctuations over short timeframes. Moreover, as Chapter 5 showed, intensive longitudinal studies, which are notably scarce compared to cross-sectional studies, tend to maintain this unitary perspective, and frequently employ non-validated measures. These two limitations impede researchers' ability to fully capture the construct's intricacies and have hindered researchers from effectively testing the dynamic assumptions inherent in theories like the Habit-Goal framework (Watkins & Nolen-Hoeksema, 2014).

For example, the Habit-Goal framework proposes that rumination arises from the activation of a habitual ruminative response style versus goal-driven processing, but the dynamics of how rumination unfolds as a habit versus goal-directed behavior over time have not been directly examined. Similarly, the role of executive control deficits in sustaining rumination has been inferred from correlations between trait rumination and performance on one-time laboratory executive control tasks, but not in daily life. Consequently, our understanding of the mechanics of rumination — its triggers, patterns, frequency, characteristics, moderators, and consequences — remains predominantly speculative, inferred from indirect evidence rather than observed directly.

These two limitations—a unitary view and a lack of studies on the dynamic nature of rumination—are particularly evident in the literature concerning the association between rumination and executive control. This literature is especially complex as these limitations add to the jingle-jangle fallacy that hinders research in executive control (see Chapter 2.1). Indeed, despite nearly three decades of research, the relationship between rumination and executive control remains unclear. Theoretical frameworks like the resource depletion account and the impaired disengagement hypothesis attempt to explain this relationship. However, given the way rumination is traditionally studied and measured, it begs the question whether past research was equipped with the appropriate tools to accurately answer their questions. Most studies exploring the associations between executive control and rumination are cross-sectional, providing no insight into causality. And, while experimental/interventional studies can inform about causality, their results are diverse and inconsistent. Moreover, past research varies in the use of trait rumination, state rumination, or both, and often overlooks the implications of these different types of measurements on the theories being tested.

In summary, the two key limitations of rumination research are (1) the predominance of unitary conceptualizations and measures of rumination that disregard its multifaceted nature, and (2) the scarcity of (intensive) temporal research investigating how rumination unfolds over time. This thesis contends that overcoming these two significant limitations is crucial for advancing our theoretical understanding of rumination. To directly address these limitations, this thesis aims to reconceptualize rumination as a multifaceted, dynamic construct and utilize intensive longitudinal methods to capture its temporal fluctuations. We will contrast our findings against existing theoretical frameworks on rumination and executive control, specifically the impaired disengagement and resource depletion account.

To this end and in order not to start completely anew, we build on the work of Bernstein and colleagues. We embrace their conceptualization of rumination as a network of interacting components, with rumination as the emergent property. This approach entails analyzing the distinct associations of these components separately, rather than summing up their scores. In this thesis, we focus on the same five features of rumination as Bernstein and colleagues (2017): *perseveration*—how much participants had been thinking about their performance; *negativity*—how negative their thoughts were; *self-criticism*—how much they had been criticizing themselves; *brooding*—how much they thought about their negative emotional experience; and *replaying*—to what extent they replayed parts of what happened in their mind. These features are grounded in Nolen-Hoeksema´s research and are also in line with the Goal-Progress theory and the research on repetitive negative thinking; they encompass both process-like features of rumination (i.e., perseveration, replaying, and brooding) and features related to thought content (i.e., negativity and self-criticism). Therefore, rather than defining the most relevant features of rumination, our goal is to leverage the network conceptualization of rumination to better understand the dynamic nature of rumination and its associations with executive control, thereby extending the research of Bernstein and colleagues.

In **Section 2**, we first explore the temporal dynamics of rumination and executive control (referred to as attention control in these chapters[1]) using different methods of analysis. To this end, we collected data from forty participants using the experience sampling method (ESM): they responded to six items, including five ruminations items and one attention control item, four times a day during fourteen days. We subsequently use this data to validate the measure and analyze this data using three complementary methods of analysis. This section directly tackles the two identified limitations of the rumination literature.

Given our aim to study the temporal fluctuations of rumination, it was crucial to develop a multifaceted momentary measure of rumination that could accurately capture these variations. Consequently, in **Chapter 7**, we develop and examine the metric properties of a multifaceted ESM measure of rumination encompassing the five previously mentioned features, using the collected ESM data. To determine whether this ESM measure captures sufficient within-person

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[1] Note that, we use the term ‘attention control’ in place of ‘executive control’ to align with the most used terminology in this literature, given our use of a single self-report item to measure it.

variability, we examine the intra-class correlations (ICCs). We also investigate the convergent validity of this ESM measure with trait rumination, depression, and anxiety questionnaires.

In **Chapter 8**, we explore the interplay between rumination features and attention control over time using a multilevel vector autoregressive (mlVAR) model. The key advantage of mlVAR is that it allows us to model the temporal dynamics between variables by analyzing their contemporaneous associations (within the same time point), temporal associations (from one time point to the next), and between-subject associations (the partial correlations of the within-person means). As per the impaired disengagement hypothesis, attention control should be associated with higher rumination at all levels (i.e., contemporaneous, temporal, and between-subjects). In contrast, the resource depletion account suggests that rumination features should be associated with poorer attention control, at the contemporaneous and temporal levels. Moreover, this study aims to shed light on the relative importance of each rumination feature, questioning whether they are all equally important or if some features are more influential. According to the network theory of rumination, if the features are distinct and non-interchangeable, we expect the features to have different levels of influence in the networks. Conversely, if all features of rumination are interchangeable, we expect them to be equally influential and interconnected.

In **Chapter 9,** we employ a different approach to investigate the temporal interplay between rumination and attention control: Transfer Entropy analysis and Active Information Storage analysis, both grounded in Information Theory. As this type of analysis has not previously been applied in psychology research, our study aims to introduce and demonstrate the utility of this novel technique. The advantage of this analysis lies in its multivariate, non-parametric nature, capable of capturing both linear and non-linear associations. Unlike the mlVAR model, it can detect temporal dependencies among several variables simultaneously at different lags, not just based on a fixed lag value (e.g., between the previous and current time points). Given the exploratory nature of this study, we do not posit strong hypotheses but rather discuss the potential of this approach to capture complex linear and non-linear dependencies. Nonetheless, we anticipate replicating, at least to some extent, the results from the mlVAR model, potentially offering support to either the impaired disengagement hypothesis or the resource depletion account. The exploratory facet of this analysis also relates to its ability to detect that several past states of a variable can help predict a variable's current state. Therefore, for some features of rumination or attention control, not just the exact preceding state but several past states may hold predictive value. We discuss the potential implications of this in the context of psychology and the dynamic interplay between features of rumination and attention control.

In **Chapter 10**, the last chapter of Section 2, we apply the affective dynamic approach to rumination. Our exploratory investigation looks at whether rumination features differ in their dynamics when considering inertia and moment-to-moment variability, and whether these metrics predict depression and anxiety symptoms. Indeed, some researchers have applied metrics typically used in affective dynamics research (i.e., inertia) to the study of rumination. However, these studies have not investigated the predictive value of metrics such as inertia of rumination compared to person-level means or standard deviations. Moreover, previous research on affective dynamics suggested that metrics such as inertia might not provide any additional predictive value beyond person-level means and standard deviations. Therefore, we aim to tackle this question in the context of rumination and its features. Using the ESM data we collected and the self-report questionnaires of depression, anxiety, and trait rumination given at the end of the ESM period, we investigated whether the inertia and moment-to-moment variability (i.e. RMSSD) of features of rumination predict depressive and anxious symptoms, even after controlling for person-level means and standard deviations. Moreover, we also aim to see whether these ESM-derived metrics of features of rumination have predictive value when compared to trait rumination. If the latter proves true, it would lend additional support to the utility of intensive longitudinal data despite its increased burden on participants.

In **Section 3**, we experimentally examine the link between executive control and rumination features using transcranial direct current stimulation (tDCS), given that our review of the literature in Chapter 2 indicated that it was a promising and non-invasive neuromodulation technique. Studies using tDCS to target executive control often chose the dlPFC as a target, usually seeking to improve executive control by stimulating the left dlPFC. As the dlPFC is also a key region involved in rumination, several studies have examined the impact of tDCS over the left dlPFC on rumination. We thus sought to investigate the impact of tDCS over the left dlPFC on rumination in the same way, but by examining the impact of the neuromodulation on the different features of rumination.

While tDCS is a promising neuromodulation technique, its use involves many degrees of freedom: researchers must choose a specific combination of parameters of stimulation, montage, intensity, etc. Consequently, tDCS studies vary greatly in their study protocols. Therefore, before conducting a tDCS study, we first conducted a systematic review of the effects of tDCS on rumination in clinical and non-clinical samples (**Chapter 11**). This systematic review aims to provide an objective view of the literature about the effects of tDCS on rumination and potentially identify the best combination of tDCS parameters and study design to influence rumination.

Based on the insights of this systematic review, we proceed to evaluate the effects of tDCS on rumination in a non-clinical sample (**Chapter 12**). We conducted a double-blind, within-subject, randomized, sham-controlled tDCS study in which the same participants as the ESM data collection participated[2]. During the tDCS stimulation, participants completed an N-back task. Following the tDCS stimulation, we measured state rumination after a stress induction and resting period; we measured it again as a multifaceted construct using the measure used by Bernstein et al. (2017) and looking at the same five features. Based on the impaired disengagement hypothesis and on previous research, we expected that (a) anodal tDCS over the left dlPFC would reduce state rumination (as a total score and on individual features), (b) that this effect would be mediated by executive control performance (i.e., anodal tDCS would improve executive control as measured by the N-back performance which in turn would lead to lower rumination during the resting period), and (c) that this mediation would be moderated

[2] Hence, in this thesis, we performed two data collections (i.e., (1) one using ESM and (2) one in an experimental setting) with the same forty participants participating in both.

by trait rumination (i.e., the higher the trait rumination, the stronger the effect will be). Moreover, it is still unclear in the literature which aspects of rumination are influenced by executive control changes and tDCS: are all features equally influenced? We therefore strive to investigate whether tDCS would differentially impact the various features of rumination.

In the general discussion (**Section 4**), I summarize our findings and highlight how they converge and diverge. I also discuss the implications of these findings considering the two theoretical/empirical limitations we wanted to address and how the findings advance our understanding of rumination, the role of executive control, and relate to existing theories and models. In addition to the theoretical implications, I also briefly discuss the clinical implications. Notably, I highlight several limitations of this thesis throughout the discussion. Finally, I propose directions for future research and outline a first version of a new formal theory of rumination that integrates its multifaceted and temporal characteristics.

Section 2.

Exploring the temporal dynamics of rumination and its associations with executive control

Chapter 7.

An experience sampling measure of the key features of rumination

Background. Research indicates that rumination can be viewed as a dynamic process that fluctuates over time, within hours and days. An increasing number of intensive longitudinal studies on rumination are accordingly being conducted and published using experiencing sampling methodology (ESM), a technique with measurements in everyday life. Yet, this literature suffers from a profound caveat: rumination has so far been conceptualized and measured as a unitary construct in these ESM studies. This is unfortunate, since such a unitary view contrasts with prominent contemporary models that regard rumination as a multifaceted construct, wherein the key features are not interchangeable and should therefore be measured separately. Moreover, no validated ESM measure of the key features of rumination has yet been developed. Therefore, we developed and validated an ESM protocol and the first ESM questionnaire to assess rumination as a multifaceted construct, measuring five key features of rumination.

Method. We conducted an ESM study in a community sample of 40 French-speaking participants. They answered the five rumination ESM items in French four times a day for fourteen days. At the end of the ESM assessment period, participants completed trait-like questionnaires of rumination, depression, and general anxiety.

Results. The ESM rumination items exhibited good psychometric properties, including excellent within-person variability and convergent validity with corresponding trait-like constructs.

Conclusions. Although further validation is warranted, this novel ESM assessment protocol of rumination as a multifaceted construct (validated in French and translated into English) will allow future researchers to study how rumination's features fluctuate and interact with other constructs over time.

Reference

Hoebeke, Y., Blanchard, A., Contreras, A., & Heeren, A. (2022). An experience sampling measure of the key features of rumination. *Clinical Neuropsychiatry, 19, 288–297.* https://doi.org/10.36131/cnfioritieditore20220504

7.1 Introduction

Rumination consists of repetitive negative thoughts about one's concerns, sensations, feelings, and their implications, without taking any problem-solving action (Nolen-Hoeksema, 1991). Although mostly treated as a stable trait-like construct (Nolen-Hoeksema & Davis, 1999), recent research indicates that rumination might be better conceptualized as a dynamic process that fluctuates over time (e.g., Fang et al., 2019; Marchetti et al., 2018a). In the last two decades, the study of the dynamics and fluctuations of psychological processes has been facilitated through the advent of technology and ecological approaches such as the Experience Sampling Methodology (ESM; Csikszentmihalyi & Larson, 1987). ESM allows for the acquisition of intensive longitudinal data (also called time-series data) and consists of measuring variables of interest daily or multiple times a day specific using various devices such as electronic diaries, watches, or smartphones (Hektner et al., 2007; Myin-Germeys et al., 2009). Researchers can thus capture the moment-to-moment fluctuations of their variables of interest with increased reliability and ecological validity (Hektner et al., 2007).

This growing interest in the daily study of psychological constructs has also become apparent in rumination research, as many ESM studies have begun to investigate the temporal fluctuations of rumination. For instance, ESM studies have revealed that an increase in negative affect (e.g., Hoorelbeke, Koster, et al., 2016; Moberly & Watkins, 2008; Takano et al., 2011) and a decrease in positive affect (e.g., Brans et al., 2013; Hoorelbeke, Koster, et al., 2016; Huffziger, Ebner-Priemer, Eisenbach, et al., 2013) often follows moment-to-moment increases in rumination. More recently, Faelens et al. (2021) found that Facebook use adversely predicted psychological processes (e.g., increased rumination), negative affect predicted more rumination at the next time point, and rumination predicted negative affect at the next time point as well (but to a lesser extent). Hjartarson et al. (2021) also found that negative affect predicted subsequent changes in rumination (increased negative affect leading to increased rumination), although they did not find evidence for the inverse relationship. In summary, ESM research has allowed researchers to explore the temporal fluctuations of rumination in more detail and thus shed light on its association with other variables.

Despite their contribution to the understanding of the dynamic nature of rumination, most of these ESM studies conceptualized rumination as a unitary construct; that is, they measured rumination via a single item or through a sum score of several self-report items (e.g., Faelens et al., 2021; Fang et al., 2019; Hjartarson et al., 2021). This is problematic since previous research and various models have pointed to distinct features of rumination, although there is no consensus regarding the exact number of features encompassing rumination. According to one of the most prominent models of rumination, the Response Styles Theory, there are at least five key constitutive features (Nolen-Hoeksema, 1991; Nolen-Hoeksema et al., 2008): namely, perseveration (the extent to which one repeatedly thinks about the same events, experiences, themes), brooding (the extent to which one thinks about the causes and consequences of their emotional state or emotional experiences), negativity (the extent to which one's thoughts are negative), self-criticism (the extent to which one criticizes themselves), and replaying (the extent to which one replays parts of events in their mind). Prior cross-sectional laboratory research has emphasized the added value of assessing these five features separately—via a specific item for each of the five features (e.g., Bernstein et al., 2017; LeMoult et al., 2013).

Moreover, in line with conceptualizing rumination as a multifaceted construct, research has shown that the five features proposed in the seminal work of Nolen-Hoeksema (Nolen-Hoeksema, 1991; Nolen-Hoeksema et al., 2008) can be viewed as nodes interacting within a complex network system (Bernstein et al., 2017, 2020). Indeed, by applying network analysis, these studies revealed for the first time the non-interchangeability of these features (e.g., Bernstein et al., 2017; Bernstein et al., 2020)—that is, though strongly interrelated, each feature was predictive of and predicted by the other ones in a unique fashion. Beyond emphasizing the relevance of distinguishing these features, these results thus suggest that each of the five features may serve a functionally distinct role and interact in a unique fashion with the other ones (e.g., the more one criticizes oneself for failures, the more likely one is to brood about how sad one feels).

However, despite these promising conceptual and empirical developments, these prior studies aiming to break down rumination into its distinct components all relied on cross-sectional data. Additionally, none of the ESM studies on rumination considered the various features of rumination (e.g., Faelens et al., 2021; Fang et al., 2019; Hjartarson et al., 2021), thus thwarting any inferences regarding the specific temporal unfolding of rumination's features. This current state of the literature on rumination is unfortunate, since enabling a temporal analysis of the five features of rumination would have at least three benefits. First, intensive longitudinal data would allow researchers to study how five hallmark features of rumination following Nolen-Hoeksema's theory (2008) unfold over time. Second, intensive longitudinal data will enable the application of several analysis methods. One promising approach that has gained traction in the last few years is temporal network analysis (for a review, Blanchard et al., 2023). Such explorations could give us insight into how these five distinct components trigger one another within participants over time while simultaneously investigating between-subjects associations. From this perspective, researchers could study how these variables self-predict from one time point to another (i.e., autoregression) and predict one another (i.e., cross-lagged regression). Moreover, inspired by research on critical transitions in ecosystems (e.g., Hirota et al., 2011), one can also use intensive longitudinal data to grant clinical insight into whether someone is about to tip into a disordered state (e.g., development or relapse of psychopathology) or return to an ordered one (e.g., recover; for more detail, see Wichers et al., 2016, 2019). Finally, one can also use intensive longitudinal data to generate idiographic (i.e., specific to a single person) network models depicting how distinct variables of interest influence one another over time within one person. Idiographic networks can thus grant information about potential clinical pathways at play for a single person (Bastiaansen et al., 2020), thereby opening up radically new vistas for quantitative individualized case conceptualization and personalized therapeutic strategies (A. J. Fisher et al., 2017; A. J. Fisher & Bosley, 2020).

Unfortunately, to the best of our knowledge, no validated ESM tool allows researchers to assess rumination's features over time. We therefore propose the first ESM measure dedicated to capturing the temporal nature of the five features of rumination. As argued elsewhere (Blanchard et al., 2021), developing ESM items widely departs from creating a traditional (single time point or 'trait') questionnaire and comes with its specific challenges. For instance, ESM surveys should be extremely brief, taking a maximum of two to three minutes to complete, since participants will be taking time from their daily lives over weeks or months to answer these questions (Eisele et al., 2022; Kimhy et al., 2012; Myin-Germeys et al., 2018; Varese et al., 2019). Next, questions should not feature too many repetitive items since participants already answer the same questions repeatedly, and participants often find answering similar items frustrating and confusing (Myin-Germeys & Kuppens, 2021). Some researchers therefore suggest employing single-item measures for straightforward unidimensional constructs (Robins et al., 2001; Wanous et al., 1997). Moreover, ESM items should be expressed in colloquial rather than technical terms so that they more closely mirror how individuals describe their daily life experiences (Myin-Germeys & Kuppens, 2021). One should therefore be extremely careful about the wording when developing ESM items (Myin-Germeys & Kuppens, 2021). In addition to careful phrasing, ESM studies need to find a balance between measurement frequency, measurement duration (i.e., the time required to answer an ESM questionnaire), and participants' burden, while also ensuring that the chosen measurement frequency adequately assesses the targeted constructs (Myin-Germeys & Kuppens, 2021). For example, asking about a participant's sleep quality three times a day is excessive; asking about a participant's appetite three times a day, however, would be suitable if timed around mealtimes. These requirements for developing optimal ESM items have rendered the assessment of their validity and reliability remarkably difficult (for an accessible overview of test reliability and validity concepts, see Jhangiani et al., 2019).

Despite these challenges, it is possible to assess the validity and reliability of ESM items by using methods appropriate for state measures. To this end, multi-level reliability, which evaluates both between- and within-person reliability, can be used to examine whether the ESM items cohere into a scale assessing the same overall construct (Cranford et al., 2006; Shrout & Lane, 2012). At the most straightforward level, one can evaluate the content validity of ESM reports by examining whether internal experiences make sense together (i.e., theoretically similar states would correlate, Eisele et al., 2021; Hektner et al., 2007). One can also examine convergent and discriminant validity by correlating ESM measures with similar and different constructs (Eisele et al., 2021). Since ESM items aim to capture fluctuations, it is also necessary to ensure that item responses have sufficient within-subject variability. To do so, one can examine each item's within-person standard deviation and intraclass correlation coefficients (ICCs; Trull & Ebner-Priemer, 2020), representing the proportion of the total variance due to between-person variance (Snijders & Bosker, 1999).

Following the above guidelines, we thus had two primary goals for the current project. First, we sought to develop an ESM tool (in both French and English) to assess five features of rumination. Since evaluating the reliability and validity of ESM measures is challenging, it is vital that the item-development phase results in self-explanatory and unambiguous items (i.e., high face validity) while covering all aspects of the construct (i.e., high content validity). We therefore carried out an iterative item development process, which included adapting items from existing one-time questionnaires into comparable measures of momentary state constructs. We developed the items in French and then back-translated them into English (see section "ESM Items & Protocol Development").

Second, inspired by recent ESM item development research (e.g., Blanchard et al., 2021), we wanted to investigate how the ESM items performed when administered to a community sample over fourteen days. To this end, we probed whether our newly developed items yielded sufficient within-person variance (i.e., low ICCs) and whether they had good convergent validity with trait-like questionnaires assessing similar constructs (see section "ESM tool psychometric properties"). If we met these goals, we wanted to share our resulting ESM items, administration methods, and all materials in an open science fashion (see below). We believe such an approach can foster further research on the temporal dynamics of rumination, facilitate direct comparisons between different studies, and provide the scientific community with a validated set of ESM items to measure the five key features of rumination over time.

7.2 Method

7.2.1 ESM Items & Protocol Development

ESM Rumination Items

To develop our ESM protocol on the features of rumination, we adapted items from previous research using a one-time measure (Bernstein et al., 2017; LeMoult et al., 2013) based on Nolen-Hoeksema's research (1991; Nolen-Hoeksema et al., 2008) and translated them into French[1]. The resulting ESM items consist of five items referring to each of the following five features of rumination: brooding, perseveration, replaying, negativity, and self-criticism (see Table 9). In particular, we reformulated the brooding and perseveration items to be more broadly applicable and more closely reflect the definition of brooding and the repetitive nature of thoughts, respectively.

Since rumination is not bound by set times or schedules but could occur at any time of the day, we tested two different prompt frequencies (four or five times a day) and, based on participants' feedback, chose four times a day (for more details about these initial pilot studies, see the supplementary materials[2] available at https://osf.io/wj6xn). We strictly separated the four assessments by four hours (i.e., 9 AM, 1 PM, 5 PM, and 9 PM) in the validation study. This time equidistance is required for many multi-level statistical analyses (Epskamp et al., 2017). Additionally, according to participants' feedback, these scheduled time points struck a balance between not starting too early in the day and not ending too late; they were also flexible enough for a broad population. Lastly, we used a back-translation procedure to translate the French ESM

[1] The authors of this paper translated and adapted the items from Bernstein et al. (2017) and LeMoult et al. (2013); we discussed the phrasing of each item to ensure they would fit an ESM study. In addition to adapting and translating the items, we also developed a short explanation for each item to ensure participants correctly understood their meaning.

[2] The supplementary materials for each chapter are also available in the Appendices.

items (and their explanation) to English (see Table S1 in the supplementary materials at https://osf.io/wj6xn for the English version of the items as well as the explanation of the items provided to participants). First, a native French speaker who was fluent in English translated the ESM items from English to French. Then, two native English speakers who were fluent in French translated the French items into English, with any discrepancies between the two translations resolved through discussion.

Table 9. Descriptive Statistics of the ESM Items

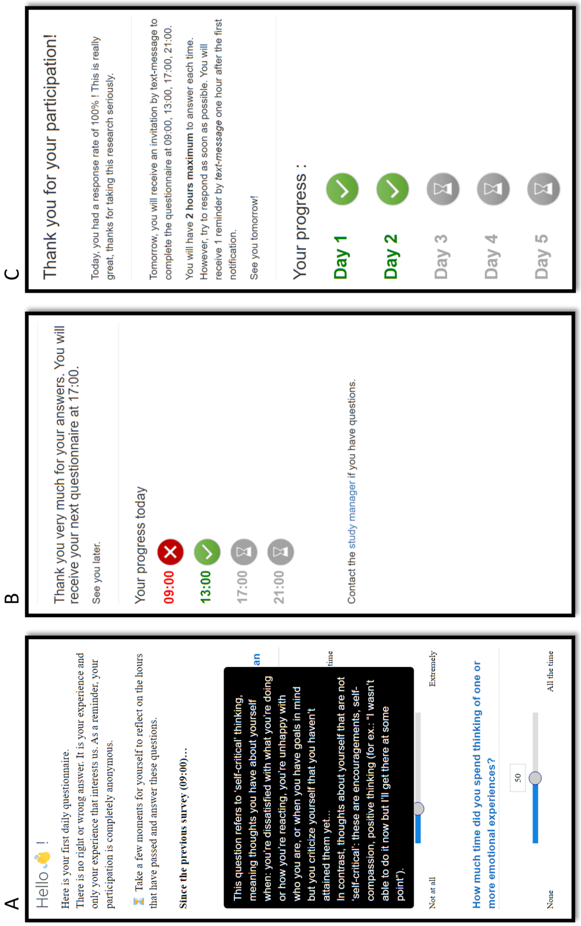
Variable	Item	*M*	*SD*	*Min*	*Max*	*ICC*
Perseveration	How much time did you spend thinking of one or more emotional experiences?	37.53	13.71	6.06	71.15	0.24
Negativity	To what extent were your thoughts negative?	27.76	13.48	0.00	62.49	0.26
Criticism	To what extent were your thoughts self-critical?	29.16	15.45	0.00	57.93	0.35
Brooding	How much did you think about the causes and consequences of emotional experiences?	33.95	14.07	5.72	67.49	0.25
Replaying	To what extent have you mentally replayed emotional experiences that you've had?	35.14	13.64	5.74	66.85	0.23

Note. This table contains the final ESM items in English (back-translated from the French items). The French ESM items can be found in the supplementary materials. *M* = within-person mean; *SD* = within-person standard deviation; ICC = Intraclass Correlation.

ESM Protocol Development

We wanted to create an ESM protocol using open-source software at a low cost. To this end, we used *formr* (Arslan et al., 2019) to collect sociodemographic and trait self-report data, and execute the ESM protocol. *Formr* (https://formr.org) is a software and study framework that allows researchers to create complex longitudinal surveys using R (R Core Team, 2022). It encourages open source practices by making studies easy to replicate (as the code for a specific study can be easily shared; see https://osf.io/dngyk/ for the code and instructions). Moreover, we chose to use *formr* because it is a web-based software: the surveys can be answered on any device with a web browser, ensuring compatibility with most of today's smartphones regardless of their operating system or brand. Another benefit of using *formr* is the extensive customization possible that allowed us to optimize our ESM protocol for compliance and optimal user experience (see the supplementary materials section available at https://osf.io/wj6xn). For instance, we customized the visual appearance of the survey and included 'tooltips' (i.e., text boxes with explanations about an item, available at any time upon clicking on a question; see Figure 15). Lastly, *formr* allows surveys to be sent through two main methods: email or text message. From our two pilots, we concluded that sending text messages was the most convenient option for the participants of this study.

Figure 15. Screenshots of the ESM Protocol Created Using Formr



Note. A: The ESM survey with a tooltip showing up; B: the screen once participants submitted an ESM survey during the day; F: End of the second day. Participants can see their progress throughout the study, and an encouragement message shows up on top depending on the day of the research and their response rate for the day.

7.2.2 ESM Tool Psychometric Properties

Participants

We gathered the ESM data between February 26th, 2021 and June 8th, 2021. Forty participants were recruited through social media (77.5% female; mean age = 21.2, *SD* = 2.03, min = 18, max = 26). To be included in the study, participants had to: be between 18 and 60 years old, be right-handed, speak French, and own a smartphone capable of opening web links to complete the survey. All participants provided written informed consent. The project received the approval of the Bio-medical institutional review board of UCLouvain (REF# 2020/057). Participants received 50€ for their participation in the study.

Measures

Self-report Trait Questionnaires. We administered the Beck Depression Inventory (BDI-II; Beck et al., 1996), the Generalized Anxiety Disorder scale (GAD-7; Spitzer et al., 2006), the Trait Anxiety Inventory (STAI-T; Spielberger et al., 1983), and the Ruminative Response Scale (RRS; Treynor et al., 2003) to assess convergent validity with trait-like proximal constructs. The BDI-II is a 21-item self-report questionnaire that measures symptoms of depression. The GAD-7 is a 7-item self-report questionnaire assessing generalized anxiety disorder symptoms. The STAI-T is a 20-item self-report questionnaire assessing proneness to anxiety. The RRS is a 22-item self-report questionnaire that measures the tendency to ruminate in response to negative affect or mood. Because half of the RRS items are related to depression, the five items corresponding to the 'brooding' subscale and the five items corresponding to the 'reflecting' subscale were used separately from the symptoms referring to depression (RRS; Treynor et al., 2003). We used the validated French versions of the scales (BDI-II; Beck et al., 1996; STAI-T; Bruchon-Schweitzer & Paulhan, 1993; RRS; Douilliez et al., 2018; GAD-7; Micoulaud-Franchi et al., 2016). We computed the total scale score for each scale, with higher score values denoting worse symptomatology (see Table 10 for descriptive statistics of the trait questionnaires). The participants answered these questionnaires at the end of the ESM procedure so that their answers could reflect their experience over the prior two weeks, thereby overlapping with the ESM period.

Table 10. Descriptive Statistics of Trait Questionnaires

Questionnaire	M	SD	Median	Min	Max	Range	Cronbach's α
GAD-7	13.25	3.81	13.50	7	23	16	0.76
BDI-II	32.80	6.90	32.00	22	55	33	0.82
Brooding	10.90	3.18	11.00	6	20	14	0.73
Reflection	9.48	2.94	9.00	5	20	15	0.71
RRS-10	20.38	5.09	21.00	11	32	21	0.77
STAI-T	45.30	11.49	44.50	26	67	41	0.92

Note. GAD-7 = general anxiety symptoms; BDI-II = depression symptoms; Brooding = brooding subscale of the RRS; Reflection = reflection subscale of the RRS; RRS-10 = comprises the brooding and the reflection subscales; STAI-T = trait anxiety.

The ESM items. The ESM survey included the five rumination items discussed above[3]. We initially developed these items in French (see Table S1 in the supplementary materials at https://osf.io/wj6xn) and then translated them into English. Table 9 depicts the English back-translated version of the items. Participants answered ESM items using a continuous scale from 0 ("Not at all") to 100 ("Absolutely") to ensure sufficient variability in responses and following previous research (e.g., Aalbers et al., 2019).

[3] Note that we also included two additional items assessing self-report executive control and self-report absorption in an activity. We included this additional assessment in the context of a larger project not reported here.

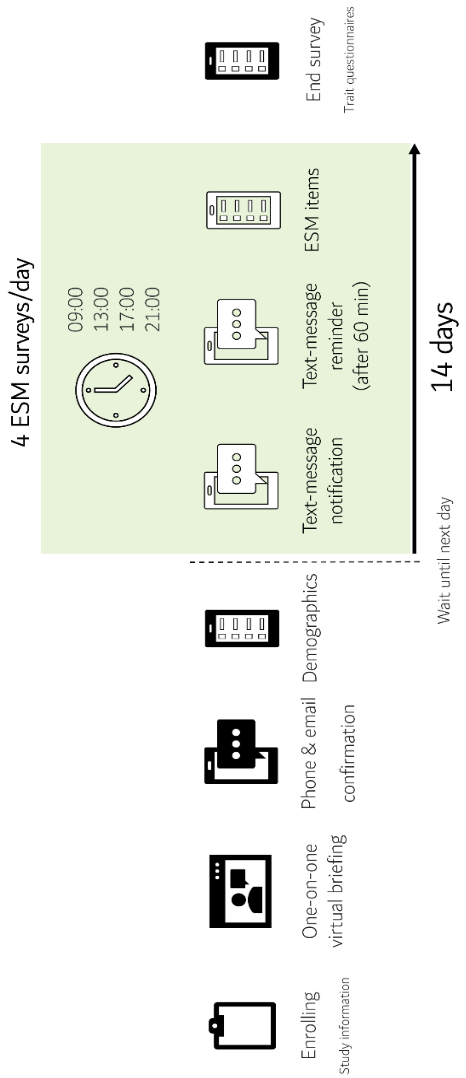
Procedure

Participants were enrolled in the study asynchronously to allow for continuous recruitment. We kept track of the number of participants and their completion rate weekly, and we stopped recruiting participants once we reached 40 participants[4] with at least a 70% completion rate. After a virtual individual briefing session (for details, see the supplementary materials section at https://osf.io/wj6xn), participants answered demographic questions on their phones and then saw a screen reminding them about the ESM procedure explained during the briefing. The ESM assessment period automatically started the next day. We used a time-contingent sampling scheme with fixed intervals: participants were prompted four times a day (at 9 AM, 1 PM, 5 PM, and 9 PM) for fourteen days. At each prompt time, participants received a text message containing a personalized hyperlink to the ESM survey. Participants received an automatic reminder after one hour if they had not yet answered the survey, and they had two hours maximum to open the questionnaire following this initial notification (see the supplementary materials at https://osf.io/wj6xn for additional details about the timeout of the surveys). Moreover, a few days into the ESM period, the first author of this study called participants at a previously agreed-upon time and day to ask whether they had any questions or encountered any issues. Lastly, after submitting each ESM survey, the participant saw a screen showing how many questionnaires and days were left in the study (see Figure 16).

After the two weeks of ESM prompts, participants completed the BDI-II, the GAD, the STAI-T, and the RRS. We also invited them to answer a survey about the ESM questions and how they experienced the ESM study (details are available in the supplementary materials at https://osf.io/wj6xn). We used a Qualtrics form to recruit participants for our research and verify inclusion and exclusion criteria. To collect the demographic, ESM, and trait self-report data, we used *formr* (Arslan et al., 2019). Figure 16 summarizes the entire study's protocol.

[4] Please note that this approach is possible given the formr.org survey framework, which allows access to participants' answers and progress while the study is ongoing.

Figure 16. Schematic Representation of the ESM Procedure



Statistical analyses

We assessed whether the item responses yielded sufficient within-subject variability and whether they showed convergent validity (i.e., how the ESM items correlated with the scores of trait questionnaires answered at the end of the ESM period; Hektner et al., 2007). We carried out all analyses using R 4.1.2 (R Core Team, 2022). Our R code and de-identified data are available at https://osf.io/dngyk/.

We computed the intraclass correlations (ICC) for every variable using intercept-only multi-level models (Gabriel et al., 2019) to assess whether the item responses yielded sufficient within-subject variability. The ICC represents the proportion of the total variance due to between-person variance (Snijders & Bosker, 1999); for example, an ICC of 0.8 indicates that 80% of the variance is due to the between-person variation and 20% to the within-person variation. For ESM research, it is recommended to have items with ICCs below 0.5, and ICCs values between 0.2 and 0.4 are common for ESM studies (Bolger & Laurenceau, 2013). This would indicate that an item has sufficient within-subject variability and that it is sensible to measure it frequently (Eisele et al., 2021). We also report the intraindividual means and standard deviations, following the recommendation of Trull and Ebner-Priemer (2020). Next, we examined the correlation table of all ESM items (within-person means for the ESM period) and trait questionnaires (general anxiety, rumination, and depression). We expected to observe moderate meaningful correlations in line with expected convergent validity (Eisele et al., 2021) despite the differences in assessment type (within-person vs. between-person) and assessment period between the ESM items (four times a day during two weeks) and the trait questionnaires.

7.3 Results

The overall compliance rate was 92.05%. Participants took a median time of 50 sec to answer[5] the ESM surveys (M = 2 min 25 sec, SD = 9 min 10 sec) and a median time of 15 min 35 sec to open the ESM surveys (M = 29 min 24 sec, SD = 31 min 18 sec; see Figures S1 and S2 in the supplementary materials available at https://osf.io/wj6xn). Moreover, there were two peaks in the opening frequency of the surveys: one shortly after the initial prompt and a second smaller peak after 60 minutes (i.e., after the reminder; see Figure S2 in the supplementary materials available at https://osf.io/wj6xn).

7.3.1 Reliability

All items' ICCs were below 0.4 and thus showed sufficient within-subject variability (Table 9).

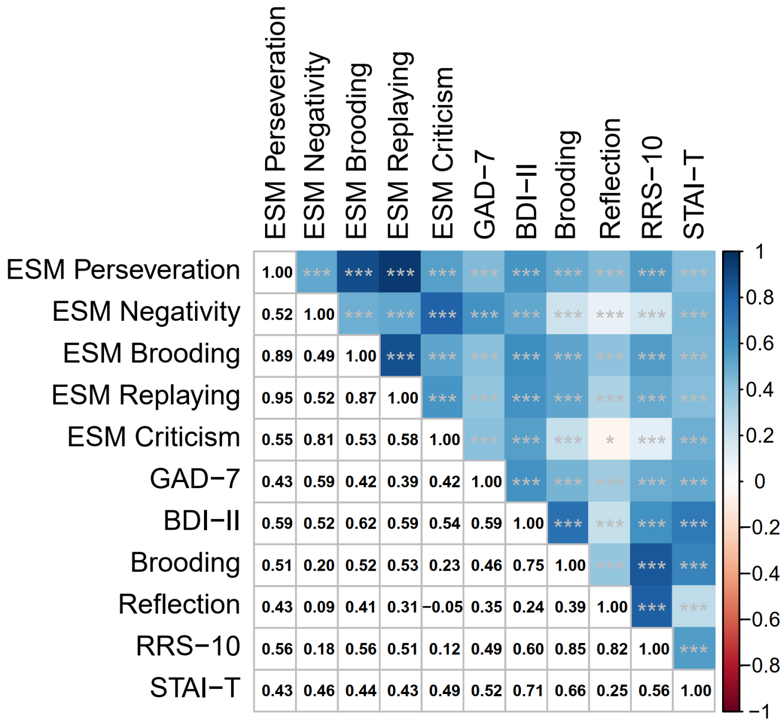
7.3.2 Convergent/divergent validity

Correlations between trait questionnaires (GAD-7, BDI-II, STAI-T, and RRS) and the within-person means of the ESM items were significant ($p < .001$) and in the expected directions (see Figure 17 for a correlation matrix). Interestingly, all rumination ESM items except "negativity" were more strongly correlated with depression symptoms (BDI-II) than anxiety symptoms (GAD-7, STAI-T). Moreover, the correlations between all ESM items and the BDI-II were higher than the correlations between ESM items and the RRS-10 (comprising only items related to rumination). Lastly, negativity and self-criticism—the only two ESM items with an

[5] We removed one observation from the dataset since the participant submitted their answer 289 minutes after the initial prompt. Moreover, four surveys have been opened more than 120 minutes after the set time points for alerts (9 AM, 1 PM, 5 PM, and 9 PM). We did not remove these observations because these delays were due to some bugs faced with *formr's* internal timing of the alerts, which induced delays from time to time (e.g., the first alert was sent at 9:25 AM instead of 9:00 AM). Hence, we decided to keep these observations.

explicitly negative connotation—had low and significant correlations with the "reflection" subscale of the RRS (reflection-negativity: $r = 0.09$, $p < .001$; reflection-criticism: $r = -0.05$, $p < .05$): this could indicate adequate discriminant validity as the reflection subscale of the RRS is considered to measure adaptive thinking patterns.

Figure 17. Correlation Plot of All ESM Variables (Within-Person Means)



Note. ESM Replaying = to what extent one has replayed parts of emotional experiences in one's mind; ESM Brooding = to what extent did one think about the causes and consequences of emotional experiences; ESM Negativity = to what extent one's thoughts were negative = ESM Self-criticism = how self-critical one's thoughts were; ESM Perseveration = how much time one spends thinking about one or more emotional experiences; GAD-7 = general anxiety symptoms; BDI-II = depression symptoms; Brooding = brooding subscale of the RRS; Reflection = reflection subscale of the RRS; RRS-10 = comprises the brooding and the reflection subscales; STAI-T = trait anxiety.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

7.3.3 Participants' experience

Participants' feedback regarding the ESM items and protocol was favorably positive (for a detailed breakdown of participants' feedback, see the supplementary materials section at https://osf.io/wj6xn). They considered that the study was not too burdensome and did not hinder their family or work life (although all but one participant were students).

7.4 Discussion

In this study, our objective was twofold: (1) to develop a low-cost and open-science ESM tool to measure rumination as a multifaceted construct over time; and (2) to evaluate the psychometric properties of this ESM tool in a community sample. Regarding our first goal, we successfully developed and tested an open-source and replicable ESM protocol, available in French and English, using *formr*. For ease of dissemination, interested researchers and practitioners can freely download the ESM protocol developed with *formr* at: https://osf.io/dngyk/. For our second goal, we recruited a community sample of forty French-speaking participants who answered the ESM survey in French four times a day over fourteen days. We found that all ESM rumination items presented high within-subject variability (i.e., all items' ICCs were lower than 0.4); it is therefore sensible to measure them frequently (Eisele et al., 2021). Correlations between the within-person means of the ESM items and the trait questionnaires of rumination, anxiety, and depression, were in the expected directions. Altogether, these results indicate that the items and the ESM tool presented here are suitable for future ESM research.

While previous studies mainly used only one or two items to measure rumination (i.e., conceptualizing it as a single construct without taking into account different key features; e.g., Faelens et al., 2021; Moberly & Watkins, 2008), the ESM items presented in this paper allow for the measurement of the five constitutive features of rumination implied by the Response Styles Theory (Nolen-Hoeksema et al., 2008). The development of these ESM items is an important step to help usher the study of rumination from a simple, static unitary construct to a more complex and multifaceted one, embracing temporal variations and interactions of these features within and between people. In doing so, future research might better understand the onset and maintenance of rumination, possibly informing new and more effective treatments for rumination.

There are some limitations, however. First, to limit participants' burden, we only included a limited number of items by sticking to one theoretical framework: five items measuring five features of rumination, whereas many more features of repetitive thought have been studied in the literature. We did not include features such as intrusiveness and uncontrollability, nor did we include other features related to the content, such as temporal orientation or abstractedness (Wahl et al., 2019). Once additional ESM items for other rumination and repetitive thought features have been validated (see, for example, Rosenkranz et al., 2020), a critical next step could be to investigate all additional features of rumination, as depicted in other conceptualizations of rumination . Such research could likely help clarify which features are most central to understanding and intervening on rumination and repetitive thoughts. This latter point is critical since there is currently no consensus on the number of relevant dimensions of repetitive negative thinking, despite the constantly evolving nature of this field (e.g., Watkins & Roberts, 2020).

Second, we only tested the items in a community sample composed mainly of students and women. Although the results and psychometric properties are promising, future studies should evaluate the psychometric properties of these items in clinical samples. Indeed, given the transdiagnostic nature of rumination across many different disorders (Aldao et al., 2010; Cavicchioli & Maffei, 2021; K. J. Hsu et al., 2015; K. E. Smith et al., 2018; Szabo et al., 2017), it is essential to verify that the ESM items perform similarly in various clinical samples. Moreover, this study only investigated the psychometric properties of the French ESM protocol with native French-speaking participants. Therefore, further research is needed to investigate the psychometric properties of the English ESM protocol (and potentially other languages) and ensure it has similar properties. Finally, our decision to send out the ESM survey four times a day seemed to strike a balance between participants' burden (i.e., low enough according to the feedback participants gave) and within-person variability (high enough according to the ICCs). However, researchers could explore different schedules (e.g., once a day, ten times a day) in future iterations.

Aside from these limitations, the ESM tool provided has several strengths. First, the ESM rumination items provide a brief and preliminarily validated way of measuring five features of rumination. This makes it possible to combine these items with other ESM items in future studies while limiting participants' burden to a minimum. Second, in addition to testing the psychometric properties of the ESM items, this paper provides a low-cost, easily replicable, and accessible open-source ESM tool. Indeed, all the necessary resources are available on OSF (i.e., a JSON file to import the ESM protocol into *formr*, the R code to pre-process and analyze the data, and detailed instructions: https://osf.io/dngyk/). One can find detailed information about the protocol in the Supplementary Materials (available at https://osf.io/wj6xn). Lastly, this ESM tool achieved high compliance (i.e., 92%) by combining several recommendations from the ESM literature (e.g., Myin-Germeys & Kuppens, 2021) with the possibilities offered by formr (see supplementary materials available at https://osf.io/wj6xn).

In conclusion, rumination is a key transdiagnostic process of mental disorders. Yet, much of the literature has operationalized rumination as a unitary trait-like construct, even though most models view it as a multifaceted state-like phenomenon, thus blocking empirical progress. In this paper, we developed and validated an ESM protocol to measure, over time, five features of rumination (brooding, perseveration, negativity, self-criticism, and replaying), as implied by the seminal model of Nolen-Hoeksema (1991; Nolen-Hoeksema et al., 2008). All of our items show good psychometric properties and sufficient within-person variability while not being too burdensome for participants. Hence, we hope that this ESM tool will help researchers usher the field forward by examining how rumination and its distinct features unfold over time and dynamically interact with other psychological processes in clinical and non-clinical samples.

Chapter 8.

Negativity is key for understanding the interplay between rumination's features, attention control, and their dynamic nature: a temporal network approach

Background. Rumination is a transdiagnostic correlate and risk factor for mental disorders. However, few studies have explored rumination and its components in everyday life, or their associations with other transdiagnostic processes, such as deficits in attention control, which may be an explanatory mechanism or consequence of rumination. Inspired by the Nolen-Hoeksema's operationalization of rumination, we investigated the associations between five features of rumination and attention control.

Method. We conducted a study relying upon experience sampling methodology: forty participants answered six items four times per day over a two-week period. Using a multilevel vector autoregressive approach, we computed three networks representing temporal, contemporaneous, and between-subjects associations.

Results. The results showed that negativity of thoughts temporally drives all other features of rumination and was the only feature impoverishing attention control over time. Negativity was also the only feature negatively associated with attention control within the same time frame. In contrast, brooding was the only rumination feature to be associated with attention control in the between-subject network (i.e., similar to cross-sectional approach).

Conclusion. These results highlight negativity as a driving force of rumination and as a potent pathway in the interplay between rumination's features and attention control. Although these results appear inconsistent with the hypothesis that impoverished attention control drives rumination, they fully align with the resource depletion account that engaging in negative thoughts depletes attentional resources.

Reference

Hoebeke, Y., Blanchard, A., Bernstein, E., McNally, R., & Heeren, A. (2023). Negativity is key for understanding the interplay between rumination's features, attention control, and their dynamic nature: a temporal network approach. *Cognitive Research and Therapy.* https://doi.org/10.1007/s10608-023-10432-2

8.1 Introduction

Everyone has experienced repetitive, negative, and self-focused thoughts like "*Why am I so sad?*" or "*Why can't I handle things better?*" Such a phenomenon illustrates rumination. It consists of repetitive, passive, self-focused thoughts about the content, causes, and consequences of one's affective state without taking any problem-solving action (Nolen-Hoeksema & Morrow, 1991). Though initially linked to depression, rumination appears best conceptualized as a transdiagnostic vulnerability and maintenance factor for affective dysregulation and related emotional disorders (McLaughlin & Nolen-Hoeksema, 2011a; Wolkenstein et al., 2014). Research has identified rumination as a viable and plausible target for transdiagnostic clinical interventions (e.g., Watkins, 2015b). Yet uncertainties remain regarding the very mechanisms of rumination, thus limiting the specificity of potential interventions.

According to prominent cognitive approaches (e.g., De Raedt, Hertel, et al., 2015; Koster et al., 2011), rumination may arise from impairments in attention control (i.e., the ability to voluntarily regulate the allocation of attentional resources). Clinical and laboratory studies dovetail with this perspective. First, empirical research has extensively documented strong associations between rumination and reduced attention control (e.g., Zetsche et al., 2018). Moreover, mounting evidence indicates that attention control can be viewed as a key transdiagnostic process of anxiety- and mood-related disorders (e.g., Coussement et al., 2022; Eysenck & Derakshan, 2011), whose improvement via clinical interventions can mitigate rumination and, in turn, alleviate depression and anxiety (e.g., Heeren & Philippot, 2011a; Hoebeke et al., 2021; e.g., Hoorelbeke et al., 2015).

Yet critical gaps remain in the literature. And one of the key issues is the conceptualization of rumination as a cohesive and unitary phenomenon, even though its definition denotes a complex and multifaceted system. For instance, the classic definition from Nolen-Hoeksema and Morrow (1991) involves perseveration, brooding, replaying, negativity, and self-critical focus. However, in empirical research, rumination has mostly been reduced to a single sum-score from a self-report measure. This approach treats each feature of rumination as interchangeable, thereby enabling researchers to tally responses to items when examining treatment effects or group differences. However, this sum-score strategy oversimplifies the story and it is easy to generate examples of how these hallmark features may interact (e.g., the more one criticizes oneself for failures, the more likely one is to brood about how sad one feels), meaning they are not interchangeable. One may also wonder how these different features differentially interact with attention control.

To fill this gap, Bernstein et al. (2017, 2020) proposed a radically different conceptualization of rumination: a network approach. Inspired by the network approach to psychopathology that posits that mental disorders can be viewed as causal systems of mutually reinforcing symptoms (Borsboom, 2017; McNally, 2016), they relied upon network analysis to examine the relationships among the five key features of the classic Nolen-Hoeksema and Morrow's (1991) theory—i.e., perseveration (i.e., the repetitiveness of one's thoughts); negativity (i.e., to what extent one's thoughts are negative); self-criticism (i.e., having self-critical thoughts); brooding (i.e., thinking of the causes and consequences of emotional experiences); and replaying (i.e., mentally reviewing parts of emotional experiences). In two studies (Bernstein et al., 2017, 2020), they found that these features were unsurprisingly strongly interrelated but not interchangeable. When each component of rumination was treated as its own entity, it appeared to relate to, influence, and be influenced by the others in different ways and to different degrees. Notably, across distinct computational network models, self-criticism consistently stood out as the most influential node within the entire network system (Bernstein et al., 2017, 2020). Moreover, in one study (Bernstein et al., 2017), they also examined the relationships among these features and tasks tapping into top-down executive control. They found that, of the five features, self-criticism seemingly drove brooding, which in turn, predicted poor executive control (Bernstein et al., 2017). However, despite their merits, these studies both relied upon cross-sectional data, thus precluding any strong inference regarding the temporal dynamics between these variables (Bringmann et al., 2022).

In addition to the conceptualization of rumination, the failure to account for rumination as a process unfolding over time is another limitation in rumination research. Most studies have relied on a cross-sectional approach, which is unfortunate given the inherently ever-changing nature of emotion regulation processes such as rumination (McRae & Gross, 2020). There is, however, a small but growing literature on the temporal dynamics of rumination (e.g., Hjartarson et al., 2021). Researchers used experience sampling methodology (ESM), which assesses pertinent variables multiple times a day over several days or weeks (Myin-Germeys et al., 2018). And the conclusions from these studies were unequivocal: rumination fluctuates over time, self-predicts itself over time (that is, from one time point to the next), and can temporally predict variables such as mood and negative affect. Yet, this research did not investigate the distinct evolution of the different features of rumination, nor how they can activate or perpetuate one another over time. Moreover, despite the assumed key role of top-down attention control in rumination research, no study has unraveled the potential interactions between attention control and the key features of rumination.

In this project, we seek to map the dynamic interplay between the hallmark features of rumination with one of its theory-driven key mechanisms: top-down attention control. To best capture the ever-changing nature of these processes, we instructed participants to report their experiences four times a day for 14 days. To characterize the dynamic associations between variables, we used a multilevel vector autoregressive model which is especially suited to visualizing temporal multivariate relationships (for a review, see Blanchard et al., 2023). Specifically, we estimated three types of networks from this high-intensive time-series dataset: 1) a temporal network to examine how variables are associated from one time point to the next; 2) a contemporaneous network to inspect how variables interrelate within the same timeframe (potentially reflecting fast-moving temporal processes occurring at a time interval quicker than the sampling interval); and 3) a between-subjects network to observe the mean-level relationships between variables collapsed across time. This threefold framework is typical practice in temporal network analysis (Blanchard et al., 2023). It can offer radically new data-driven insights into rumination.

8.2 Method

8.2.1 Data Availability and Openness

De-identified data, R script, and other supplemental materials have been made publicly available via the Open Science Framework at https://osf.io/k5dyf/. All participants provided written informed consent. The project received the approval of the UCLouvain biomedical review board (REF# 2020/057). All participants provided written informed consent. Participants received 50€ for participating in the entire study.

8.2.2 Participants

We recruited 40 French-speaking Belgian participants (aged 18–26 years, M = 21.2, SD = 2.03, 77.5% female) from the general community via social media and listserv advertisements (see Supplemental Materials for how we determined our sample size and inclusion criteria). Participants had, on average, 9.18 (SD = 1.72) years of education (after elementary school).

8.2.3 Measures and Procedure

We used a time-contingent sampling scheme with fixed intervals: participants received text messages four times a day at 09:00, 13:00, 17:00, and 21:00 with a link to the survey, over 14 consecutive days. It resulted in 56 assessment per participant, consistent with recent guidelines regarding the requisite number of timepoints for temporal network research (Blanchard et al., 2023).

The ESM survey consisted of 6 items, with five focusing on key features of rumination (i.e., perseveration, negativity, self-criticism, brooding, replaying) and one on attention control (i.e., ability to control attention when dealing with distractors). All items appear in the legend of Figure 18, and the ESM survey instructions appear in the supplementary material section (Table S2 and Table S3). Items were assessed with a slider scale from 0 (not at all) to 100 (absolutely), delivered using *formr* (Arslan et al., 2019) that allows creating complex longitudinal surveys with R. Table 11 contains the descriptive statistics of all the ESM items. Of note, further information about the psychometric development of the items depicting the five key features of state rumination is available elsewhere (i.e., Hoebeke et al., 2022).

Table 11. Descriptive statistics of the ESM items

ESM item	*within-person mean*	*within-person SD*	*ICC*
Perseveration	37.38	14.01	0.24
Negativity	28.45	13.02	0.24
Brooding	33.91	14.33	0.25
Replaying	34.93	13.82	0.23
Self-Criticism	30.00	15.12	0.33
Attention Control	58.74	12.23	0.17

Note. ICC = Intra-class correlation.

8.2.4 Data Analysis

We used a multilevel vector autoregressive model (mlVAR). Data were analyzed using R via the *mlVAR* (Epskamp et al., 2017) and *qgraph* (Epskamp et al., 2012) packages. We estimated the multilevel VAR model (generating contemporaneous, temporal, between-subject networks) through sequential estimation of univariate multilevel regression models, and we allowed the random effects to be correlated (Bringmann et al., 2013). For the contemporaneous and between-subject networks, we used the "and" rule: for an edge to be kept in the final network, both coefficients (from node A to node B and vice-versa) had to be significant (see Supplemental Material for further analyses). Based on Shapiro-Wilk tests, all within-person means were normally distributed ($p > 0.05$), but the residuals of the mlVAR model were not ($p < 0.05$). We also confirmed the stationarity of our data by using the Kwiatkowski–Phillips–Schmidt–Shin test (KPSS; $p > 0.05$ using a Bonferroni correction). We also computed the within-person mean, the standard deviation, and the intraclass correlation (ICC) of each item (see Table 11). The ICC represents the proportion of the total variance due to between-person variance (Snijders & Bosker, 1999).

8.3 Results

We excluded one participant who had a variance and mean of zero on two items, and removed one outlier response with a response time of 289 minutes. In the end, 2013 observations were kept (average compliance rate = 92.17%; mean response time = 2.45 min; median response time of 0.82 min). The mean time between two measurement completions within a day was 3 hours and 55 minutes.

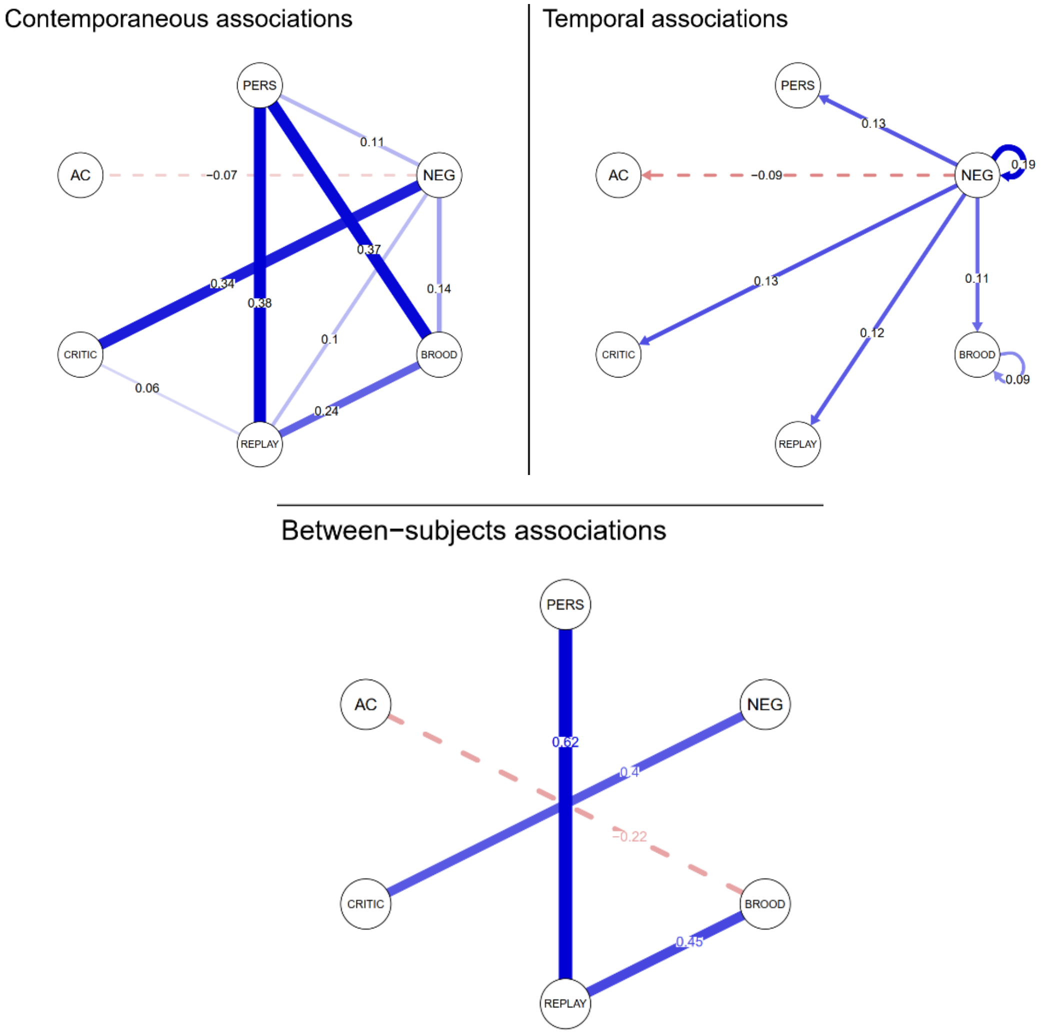
8.3.1 Network Analysis

Contemporaneous network. The features of rumination are positively associated at the same time point (see Figure 18): (1) perseveration was the most strongly associated with brooding and replaying, and (2) criticism and negativity were strongly associated as well, whereas they share small associations with replaying, brooding, and perseveration. There is no association between criticism and perseveration. Finally, attention control is negatively associated with negativity: more negative thoughts are associated with a lower ability to ignore distractions within the same time point.

Temporal network. As shown in Figure 18, negativity appears as the most influential variable. Negativity is the only variable associated with other variables at the following time point: more negative thoughts at one timepoint are associated with greater critical, replaying, and perseverative thoughts, as well as lower attention control, at the next time point. Moreover, only negativity and brooding show positive autocorrelation over time (i.e., a variable self-predicting itself from one time point to the next), with the autocorrelation of negativity emerging as the largest arrow in the entire network.

Between-subjects network. The between-subject network (Figure 18) indicates that participants with higher average negativity also have higher average self-criticism, and that higher average perseveration is associated with higher replaying. Attention control is only associated with brooding: lower average attention control is associated with higher average levels of brooding.

Figure 18. The contemporaneous, temporal, and between-subject networks



Note. AC = attention control (i.e., "When I wanted to deliberately concentrate on something, I was capable of ignoring environmental distractions (noise, notifications, visual distractors, …)"), PERS = perseveration (i.e., "How much time did you spend thinking of one or more emotional experiences?"), NEG = negativity (i.e., "To what extent were your thoughts negative?"), CRITIC = criticism (i.e., "To what extent were your thoughts self-critical?"), REPLAY = replaying (i.e., "To what extend have you mentally replayed emotional experiences that you've had?"), BROOD = brooding (i.e., "How much did you think about the causes and consequences of emotional experiences?"). Solid blue lines represent positive associations; striped, red lines represent negative associations. The contemporaneous network depicts the associations between variables within the same time frame after controlling for all other temporal and contemporaneous associations. The temporal network represents the extent to which nodes predict themselves (i.e., autoregression) and each other from one time point (t) to the next time point (t + 1). The arrow depicts the direction of prediction. The between-subject network shows the correlations between the person-level means of each variable for each participant (i.e., the average response of each participant for each variable over the course of the fourteen days).

8.4 Discussion

Rumination appears to be a key transdiagnostic risk factor for mental disorders. Yet, despite the clinical relevance of rumination, little is known about its temporal and multifaceted nature. In this study, we sought to fill this gap by examining the dynamic temporal interplay between attention control and five features of rumination, as suggested by the prominent Nolen-Hoeksema and Morrow (1991) approach. By generating networks from intensive ESM time-series data, we aimed to offer a novel perspective on the complex and dynamic interplay between rumination's features and attention control.

Overall, our results dovetail with prior literature on rumination. In line with the cross-sectional studies of Bernstein et al. (2017, 2020), we found that the five features of rumination emerge as a coherent network system (i.e., each variable was connected to at least one other variable), but, for the first time, extended this observation to the temporal realm. Our findings thus support a vision of rumination as a network system of interacting features that evolves dynamically over time. Yet not all nodes were equally important. Negativity in particular emerged as the strongest predictor of other nodes and of itself in the temporal network. This suggests negativity might act to kickstart the key features of rumination.

Our observation that the negative valence of thoughts could be a key pathway in triggering the entire network system of rumination also fully aligns with the key role of negative affect posited by several prominent theories of rumination (e.g., Nolen-Hoeksema, 1991; Watkins & Nolen-Hoeksema, 2014). Likewise, prior research has emphasized the pivotal role of negativity content induction in the emergence of rumination, and particularly vis-à-vis brooding (Ciesla & Roberts, 2007). Moreover, our observation of negativity as the rumination feature exhibiting the strongest autoregression (i.e., self-predicting itself over time) echoes early ESM findings of negative affect as strongly self-predicting itself over time (e.g., Koval et al., 2013). From a clinical viewpoint, one may thus wonder whether an intervention that specifically targets negativity might lead to a beneficial cascade of downstream benefits, reducing rumination overall. Another key next step would be to examine whether negativity constitutes a prodromal sign of maladaptive rumination and, in turn, of the instigation of mood and related disorders.

Because researchers have long postulated and studied associations between rumination and attention control, we also examined the relations between the features of rumination and attention control. One of the most striking findings was that negativity was the only feature that affected attention control over time; it was also the only feature associated with attention control in the contemporaneous network. In contrast, this association no longer appeared in the between-subjects network when the relationships between all variables are pooled across time (i.e., similar to cross-sectional approach), wherein attention control was negatively associated with the brooding feature. Of note, this observation replicates Bernstein et al. (2017) who reported a strong negative association between brooding and attention control in their cross-sectional, between-subject network study. Since this unique role of brooding only emerged in the between-subject network, it might also suggest a more trait-level relationship in the case of brooding (i.e., people more prone to brooding may also be more prone to struggling with attention control), whereas a more state-level relationship with attention control seems to occur in the case of negativity (i.e., the momentary experience of negative thoughts may concomitantly hamper attention control). Taken together, this set of observations suggests that the way rumination connects to attention control might vary across timescales — a phenomenon worthy of further elucidation (e.g., some statistical models are more precise in understanding how time intervals impact associations, such as continuous-time approach; Ryan et al., 2018).

The present study has theoretical implications. Because our results suggest that negativity is a potential trigger for attention control impairments, our findings are at odds with the well-known hypothesis that rumination may arise from impaired attention control (De Raedt, Hertel, et al., 2015; Joormann, 2010; Koster et al., 2011). In contrast, our results are consistent with the limited but consistent literature on the resource depletion account, which posits that engaging in negative thoughts depletes limited attentional resources that accordingly become unavailable for concurrent tasks (e.g., Connolly et al., 2014; Curci et al., 2013; Levens et al., 2009; Philippot & Brutoux, 2008). For example, our results dovetail with experiments showing that inducing negative thinking almost immediately depletes general attentional resources (Philippot & Brutoux, 2008). When carefully inspecting this literature, we realized that perhaps one of the most striking key differences between these two competing approaches might be the type of information to which top-down attention control is directed. Whereas most studies supporting the hypothesis that rumination arises from impaired attention control have focused on attention control during processing self-referential information (e.g., Joormann 2010; Koster et al., 2011), those of the resource depletion account have not. Instead, these studies, like ours, assessed general attention control irrespective of the content of the information processed. A crucial step would therefore be to clarify whether the directions of temporal associations between rumination and poor attention control differ according to the self-referential versus general nature of the processed information.

Several other issues require further research. First, our sample was unselected and included mainly women aged 18 to 26 years. A key step would therefore be to investigate whether the present results can be generalized to more diverse samples in terms of age, gender, and clinical status. In particular, one might wonder how variables such as age groups or psychiatric diagnoses (e.g., depression) might impact the associations between attention control and rumination features. Second, we used a single item per node, which may raise concerns about the reliability and validity of our measures. For instance, the "attention control" item could be controversial as previous research has cast doubts on self-report measures of attention control (e.g., Quigley et al., 2017). On the other hand, self-report measures of attention control sometimes yield more comprehensible findings than lab-based measures (e.g., McNally et al., 2013). Moreover, research has shown that single-item measures can have good predictive validity and reduce participant burden by keeping surveys brief (Song et al., 2022), and the excellent psychometric qualities of the ESM items used in this study were reported elsewhere (Hoebeke et al., 2022). Future studies could also include brief computerized tasks measuring attention control, though administrating reliable computerized tasks assessing attention control four times a day may discourage participants. Moreover, our item measuring attention control does not cover all the facets of attention control. For instance, we did not distinguish between situations wherein attention is distracted by internal thoughts (e.g., intrusive thoughts, memories, somatic experiences) versus external stimuli (e.g., phone notifications).

Finally, although most prominent cognitive models of rumination consider it a regulatory emotional stress response, we unfortunately did not assess stress. The only prior cross-sectional network study on the interplay between the five features of rumination and attention control (i.e., Bernstein et al., 2017) did include a single social stressor. Instead, in our study, participants' rumination episodes were likely triggered by naturally occurring events from their daily life, and perhaps by an accumulation of diverse stressors. Since Bernstein et al. (2017) identified self-criticism as a central pathway in the network and that we did not, one may wonder whether this discrepancy might not result from the different types of stressors used in these studies.

In summary, our findings provide data-driven clues to the temporal and dynamic underpinnings of the interplay between key features of rumination and AC. Although the current findings need to be replicated and further investigated, the present study underscores the importance of rethinking the associations between rumination features and attention control through a temporal network approach. Moreover, our results highlight the critical role of negativity as a trigger for rumination and its detrimental effects on attention control over time.

Chapter 9.

Information theory and time series in psychology: transfer entropy and the case of rumination and attention control

Background. Research in psychology turns towards embracing the complexity of mental health by conceptualizing it as a complex dynamic system. Yet, existing and commonly used analysis methods are inadequate to address psychological processes' complex, dynamic, and non-linear nature. Therefore, we sought to introduce a new type of analysis for intensive longitudinal studies based on Information Theory. We used multivariate transfer entropy to study the dynamic interplay between two key processes: attention control and rumination. These two processes have often been associated in the literature, yet the direction of their associations remains unclear.

Methods. We reanalyzed existing time-series data of a study in which forty healthy participants answered six items measuring rumination features and attention control four times a day for 14 days. We used the multivariate transfer entropy algorithm implemented in the IDTxl python package.

Results. Results indicate that the negativity and self-criticism features predicted the perseveration and replaying features of rumination which in turn predicted attention control within the same time point. Negativity and self-criticism predicted each other, and their active information storage values indicated that these features might reflect stable and less context-dependent tendencies. In summary, rumination negatively affected attention control, but not the opposite.

Conclusions. These results illustrate how multivariate transfer entropy proves useful in studying complex temporal dynamics occurring at different lags, capturing non-linear associations and both synergy and redundancy effects. Multivariate transfer entropy is a promising and might open new possibilities for researchers interested in the temporal dynamics of psychological processes.

Reference

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9.1 Introduction

Mental health research is undergoing a paradigm shift as the complexity of psychological phenomena becomes increasingly recognized. Psychological disorders and processes are now conceptualized as complex systems arising from intricate interactions between biological, psychological, and social factors unfolding dynamically over time (Borsboom et al., 2022; Fried & Robinaugh, 2020). Identifying the right variables and analytical methods to study the complexity of mental health is key within this emerging framework.

Among the many factors within this complex system, rumination and attention control are especially notable given their significance across various mental health conditions (K. J. Hsu et al., 2015; Snyder et al., 2019; Watkins & Roberts, 2020). However, our understanding of these processes, their interaction, and their role in mental health is restricted by conventional statistical tools and methodologies. While these methods are readily available, they often account only for linear relationships and are mostly used with cross-sectional, experimental, or longitudinal data. Any inferences are limited to observations: (1) based on data at one time point which only enable to describe correlations but do not permit the understanding of cause-and-effect relationships, whereas the associations they do unearth may be spurious (Hamaker et al., 2018; Molenaar, 2004); (2) based on data from a restricted context such as a laboratory setting which lacks ecological validity and often focus on a very narrow set of variables; (3) based on longitudinal data, with long intervals between measurements (i.e., months and years), which fail to capture the feedback loops typically involved in complex systems. Thus, these methods inadequately address the complex, dynamic, and non-linear nature of psychological processes.

In contrast, ongoing advancements in technology and data collection methods, such as the Experience Sampling Method (ESM; Myin-Germeys et al., 2018) offer a promising solution to these limitations. Researchers are now better equipped to collect data at shorter intervals (i.e., separated by mere minutes or hours) and conduct intensive longitudinal studies. These studies yield more comprehensive data and foster the development of temporal dynamic analysis methods like growth curve modeling (Curran et al., 2010), multilevel vector autoregressive models (Epskamp, Waldorp, et al., 2018), and dynamic structural equation modeling (Hamaker et al., 2018). While these methods represent a step forward, they often still assume linear associations, emphasizing the need for exploratory methodologies capable of capturing both linear and non-linear relationships.

Consequently, we stand at a crossroads in our understanding of mental disorders. Although the theoretical groundwork supports a complex systems perspective, the question remains: how do we effectively study this complexity? This dilemma becomes evident when we examine the literature on the associations between attention control and rumination. Despite three decades of intensive research, their causal associations remain unclear.

Therefore, this paper aims to examine one tool to address some aspects of this dilemma: that is, multivariate Transfer Entropy (mTE), which has been used in a variety of fields such as in neurosciences (Harmah et al., 2020) and economics (García-Medina & Hernández C, 2020).

We propose using this method to elucidate the complex dynamics between psychological processes and apply it to the study of rumination and attention control. We offer a succinct overview of the research surrounding these two processes, pinpointing limitations, and underscoring the need for novel analytical approaches to multivariate time-series data of psychological processes. Subsequently, we delve into Information Theory and introduce Transfer Entropy as a non-parametric, multivariate analysis method capable of accounting for lagged linear and non-linear associations.

Rumination and Attention Control are prime examples of psychological processes that can benefit from intensive longitudinal research and multivariate time-series analysis. Rumination is a common symptom of depression, anxiety, and other mental disorders (McLaughlin & Nolen-Hoeksema, 2011a; Watkins, 2015a). It consists of negative, repetitive thoughts about one's preoccupations and their causes, meanings, and consequences, without taking action to resolve them (Nolen-Hoeksema et al., 2008). Attention control—alternatively termed cognitive control or executive control—is an umbrella term that refers to high-level, complex processes that allow individuals to efficiently organize and regulate a series of attentional and cognitive processes (Baddeley, 1992; Norman & Shallice, 1986) depending on the situation and their goals (Miller & Cohen, 2001). As attention control affects both actions and thoughts, its relationship with rumination has been extensively studied.

Numerous studies have linked increased rumination with attention and executive control deficits (Vălenaş et al., 2017; Yang et al., 2017; Zetsche et al., 2018). However, the cross-sectional and correlational nature of this evidence does not elucidate the manner or reasons why attention control deficits correspond with an increased tendency to ruminate. Two opposing hypotheses have been proposed. The *impaired disengagement hypothesis* (Koster et al., 2011) suggests that impaired attention control makes it difficult to discard no longer relevant information from working memory, causing negative thoughts to proliferate and prolong rumination. Experimental evidence and longitudinal evidence support this hypothesis (Demeyer et al., 2012; Ng et al., 2022; Ronold et al., 2020; Zetsche & Joormann, 2011; Zwalmen et al., 2023). In contrast, the *resource depletion account* of rumination proposes that rumination consumes cognitive resources, thereby impeding efficient resource allocation (Hertel, 2004; Kofta & Sedek, 1998; Levens et al., 2009). Supporting this hypothesis, induced short-term rumination has been found to disrupt executive functioning (Philippot & Brutoux, 2008; Watkins & Brown, 2002) and only one longitudinal study that investigated the resource depletion account found that baseline rumination predicted poorer executive functioning at a 15-month follow-up, while baseline executive functioning did not significantly predict rumination at follow-up (Connolly et al., 2014). Overall, the majority of research offers support to the impaired disengagement hypothesis, yet little evidence contradicts the resource depletion account since it has been less investigated.

In light of this literature, Bernstein and colleagues (2017) proposed that how rumination is conceptualized may be hindering further progress in the field. Up until now, studies have mainly treated trait rumination as a unitary construct, often measured using sum-scores or a few dimensions (e.g., brooding vs. reflection, Treynor et al., 2003). This approach is also evident in state measures of rumination employed in experimental research, such as the Brief State

Rumination Inventory (e.g., the Brief State Rumination Inventory (BSRI); Marchetti et al., 2018a) and ESM studies (e.g., Blanke et al., 2021; Moberly & Watkins, 2008). In contrast to this 'unitary' perspective, Bernstein et al. (2017) proposed to reconceptualize rumination as a network of components, akin to how mental disorders have been reconceptualized as networks (Borsboom, 2017). In their studies, Bernstein and colleagues (Bernstein et al., 2017, 2020) measured five distinct features of state rumination. They found strong associations between these features while also highlighting their non-interchangeability. Notably, these five features of rumination demonstrated distinct relationships with executive functions (Bernstein et al., 2017).

Until recently, this conceptualization of rumination as a network system of interacting elements had only been examined in an experimental lab setting (Bernstein et al., 2017) or cross-sectionally (Bernstein et al., 2019). Hoebeke et al. (2023b) took a different approach by studying rumination in a more dynamic setting using the Experience Sampling Method. In their study, they examined self-reported state rumination and attention control four times a day over a period of fourteen days in a community sample consisting of forty participants. Notably, instead of relying on a composite score or a single item to gauge rumination, they measured five features of rumination adapted from Bernstein and colleagues (2017). The analysis revealed that the extent to which one's thoughts were negative not only positively predicted itself but also the other features of rumination at the next time point. Furthermore, this negativity inversely predicted attention control at the subsequent time point. This result is the first of its kind suggesting that rumination leads to worse attention control in daily life in healthy subjects, thereby supporting the resource depletion account.

Hoebeke et al. (2023b) used a multilevel vector autoregressive model (mlVAR; Epskamp, Waldorp, et al., 2018). This kind of temporal multivariate network analysis uses mixed models to analyze the (1) temporal associations and (2) contemporaneous associations. The temporal associations represent the extent to which variables at a time point t-k predict a variable at a time t, with k being any given number of lags, typically set to 1. The contemporaneous associations represent the associations between all the variables at one time point, accounting for the temporal associations. The mlVAR has been increasingly used in psychological research (Blanchard et al., 2023) thanks to its ability to capture dynamic lagged relationships and account for individual differences, as it allows for both fixed and random effects. However, mlVAR models presume multivariate normality and that all relationships between variables are linear. This assumption can be somewhat restrictive, particularly as some researchers suggest that psychology is more accurately described as a complex system with nonlinear associations (Borsboom et al., 2022).

In the following paragraphs, we will present a non-parametric measure derived from Information Theory, known as multivariate transfer entropy. This measure is utilized to infer temporal relationships between various processes within a system. Unlike mlVAR, it does not make assumptions about data distribution and captures both linear and nonlinear dependencies. We will first provide an overview of Information Theory, as this theory is not widely used in psychological research. Subsequently, we will introduce transfer entropy.

Claude Shannon, often regarded as the "father of information theory", revolutionized the field of communication through his mathematical work. He devised a quantifiable measure, named *surprisal* (also known as information content, Shannon information, or self-information) to assess the amount of information exchanged when two entities communicate via a specific channel. Shannon deduced that how much information is contained in data is determined by how surprising the data is. For instance, consider two events: (1) snowfall in Dubai, (2) snowfall in the North Pole. The first event is decidedly more surprising (less probable) than the second one. Consequently, from an information-theoretical perspective, one would argue the first event conveys more information.

The concepts of information and surprise closely relate to uncertainty. Low uncertainty (low surprise) equates to having a lot of information, while high uncertainty indicates a lack of information. Therefore, surprising, unlikely events convey a lot of information: they allow rational agents to adapt their beliefs and expectations about the future—something they would not have done if faced with an unsurprising event. For instance, if your usually silent dog suddenly starts barking loudly, you might question why it is barking. But, if your dog frequently barks without apparent cause, you'd be less surprised by its barking and less inclined to investigate why. To summarize, uncertainty reflects an information deficit and information decreases uncertainty—they are essentially two sides of the same coin. These basic principles have spurred the development of a wide range of information-theoretic measures which have been used in diverse fields, such as biomedical signal analysis (Valente et al., 2018), stock markets (Sheraz et al., 2015), EEG data (Jin et al., 2011), feature selection in machine learning (Palamidessi & Romanelli, 2020), and data clustering (Ferenci & Kovacs, 2014).

Despite wide applications in fields like biomedical signal analysis and machine learning, the use of information-theoretic measures in psychology has been relatively scarce. From the 1950s, psychological researchers used information theory to characterize reaction times as a function of information transmitted from the stimulus to the participant, but this approach was later abandoned (Laming, 2001). The interest in information theory in psychology waned while it continued to develop in neurosciences with the advent of neuroimaging techniques (Dimitrov et al., 2011). Luce (2003) addressed the question of "Whatever happened to information theory in psychology" with skepticism, noting that until that time, applications of information theory to psychology were mostly inconclusive. More recently, Laming (2010) critically reviewed information theory applications in psychology, identifying three application categories, one of which directly relates to this article's premise. He described this category as "information theory as a technique for investigating the behavior of complex systems, analogous to systems analysis of physical systems" (p. 763). According to Laming, this application of information theory "[…] has great, as yet unexploited, potential." (p. 763).

Since then, some studies used a measure of entropy to explore how the interplay between affect and rumination predicts depressive symptoms and trait rumination (Fang et al., 2019; Koster et al., 2015). While surprisal is a measure of the information of a single event, like the roll of a dice, (Shannon) entropy is a measure of the average information (or surprisal) expected from any observation of a random variable—for example, multiple dice rolls. In essence, it is a measure of uncertainty, complexity—the more complex a data source, the higher its entropy—and randomness. These two studies found that the joint entropy of rumination and affect—the unpredictability in transitions among the occurring states—could predict depressive symptoms and trait rumination, but the results were mixed.

Although compelling, these studies are limited in their scope due to two key characteristics. First, rumination was treated as latent unitary variables, represented by the summed scores of two items (i.e., the extent to which one thought about (1) problems and (2) emotions). Second, they used bivariate joint entropy, essentially a descriptive measure of the complexity of the interaction between rumination and affect across a person's time series. This descriptive measure of the complexity of the interplay between affect and rumination is useful to compare values between people in the same way as person-level means. However, it does not inform about temporal dependencies between rumination and affect.

To capture these temporal dynamics, *multivariate transfer entropy* (mTE) is more appropriate. Transfer entropy differs from (Shannon) entropy as it measures the probability of state transitions—how a system evolves over time—instead of focusing on static probabilities (Schreiber, 2000). Simply put, transfer entropy quantifies how changes in one variable, say X, can predict changes in another variable, Y, over time. It quantifies the degree of uncertainty reduced in the future value of Y by knowing the past states of X, given the past values of Y. In other words, transfer entropy is a measure of the "new" information that X provides (on average) about the future of Y. It considers both linear and nonlinear dependencies and is a model-free measure: one does not need to presume any specific model to uncover the effects of the studied systems, even lagged effects. Initially defined for discrete data (Schreiber, 2000), it was later extended to continuous variables (Kaiser & Schreiber, 2002).

Furthermore, in contrast to bivariate transfer entropy (Schreiber, 2000), mTE has several advantages. Multivariate transfer entropy can remove redundancies such as common driver effects and pathway effects and can account for synergies such as gating effects or interacting effects. It also does a better job of retrieving ground truth in models (Novelli & Lizier, 2021). Although primarily used in neuroscience research (Wibral, Vicente, et al., 2014), transfer entropy has been used in diverse fields including financial markets analysis (Dimpfl & Peter, 2012; Scagliarini et al., 2020), health monitoring (Nichols et al., 2005), music (Kulp & Schlingmann, 2009), chemistry (Bauer et al., 2007), and ecology (Sironen, 2020).

Transfer entropy offers two distinct advantages for psychological research. First, transfer entropy captures dependencies at different delays. For example, in studying the association between stress and rumination, it is common for individuals to ruminate about stressful events that occurred hours but also days earlier. Transfer entropy can capture these lagged dependencies, providing quantifiable insight into the impact of stress on rumination over multiple past time lags, not just a single specific lag. Second, transfer entropy captures cumulative effects. A person might easily brush off a single instance of adversity in a week, without much rumination. However, when adversity and stressful events occur daily, culminating in constant stress, this could lead to more sustained rumination. It is not solely the most recent stressor but the cumulative impact of all recent stressors that counts. Transfer entropy can quantify this, considering an individual's history of stressful events when predicting future rumination.

Transfer entropy is useful to understand the flow of information from one process to another over time. However, it is crucial to note its inherent limitation: it does not measure causal effects but measures predictive transfer information: "Predictive transfer refers to the amount of information that a source variable adds to the next state of a destination variable; i.e. 'if I know the state of the source, how much does that help to predict the state of the destination?'" (Lizier & Prokopenko, 2010, p. 605). Transfer entropy does not answer the question whether a source variable directly influences the next state of a target variable. Instead, it can be viewed as a nonlinear extension of "Granger causality": any variable X that helps to predict the state of another variable Y after accounting for the past of that variable Y is considered to "Granger cause" that variable (Barnett et al., 2009). Another limitation is that information theoretic measures do not provide information about the nature of the associations it uncovers: it only indicates that one variable provides information about another variable but it does not indicate whether an increase/decrease in one variable predicts an increase/decrease in another variable. Therefore, transfer entropy analysis is best combined with other analyses depending on the research goals.

Lastly, active information storage complements transfer entropy (Faes et al., 2011; Lizier et al., 2012; Wibral, Lizier, et al., 2014). While measures like autocorrelation correspond to the extent to which a state of a variable is associated with its next state (i.e., one lag), active information storage has a broader scope. It quantifies the total dependence between the current state of a variable and all its previous states taken together (i.e., all state up to i lags), capturing both linear and nonlinear effects. Active information storage gauges the average information derived from k past states of a variable X that is useful for predicting its next value.

The goal of this study is to reanalyze the intensive longitudinal data on the features of rumination and attention control from Hoebeke et al. (2023b) using *multivariate transfer entropy and active information storage*. In doing so, we aim to apply for the first-time transfer entropy analyses to psychological self-report time-series data to better understand the dynamic interplay of attention control and five features of rumination and illustrate how this method of analysis could be useful for psychological research.

9.2 Method

9.2.1 Participants

Forty French-speaking Belgian participants (aged 18–26 years, M = 21.2, SD = 2.03, 77.5% female) were recruited from the general community via social media and listserv advertisements to participate in a larger study. Only the ESM part of this data collection is reported here. Participants had on average 9.18 (SD = 1.72) years of formal education (after elementary school) and all but two participants were students (i.e., one participant was self-employed, and another was employed). They received 50 euros for their participation in the entire study.

9.2.2 ESM Protocol

The ESM protocol used a time-contingent sampling scheme with fixed intervals: participants received text messages four times a day at 09:00, 13:00, 17:00, and 21:00 with a link to the survey. The ESM survey consisted of 6 items, with five focusing on key features of rumination and one on attention control. This measure of state rumination comprised five items: perseveration (i.e., "How much time did you spend thinking about one or more emotional experiences?"), negativity (i.e., "To what extent were your thoughts negative?"), criticism (i.e., "To what extent were your thoughts self-critical?"), replaying (i.e., "To what extend have you mentally replayed emotional experiences that you've had?"), brooding (i.e., "How much did you think about the causes and consequences of emotional experiences?"). The development procedure for these items and their psychometric properties are detailed in Hoebeke et al. (2022). We used the following item to measure self-reported attention control: "When I wanted to deliberately concentrate on something, I was capable of ignoring environmental distractions (noise, notifications, visual distractors, ...)". Items were assessed with a slider scale from 0 (not at all) to 100 (absolutely), delivered using formr (Arslan et al., 2019) that allows creating complex longitudinal surveys with R.

9.2.3 Data analysis

We conducted the data analysis in RStudio, version 2022.12.0 Build 353, using R 4.2.2 (R Core Team, 2022), JAVA 18, Python 3.1, the Java Information Dynamics Toolkit (JIDT; Lizier, 2014) and the Information Dynamics Toolkit XL (IDTxl; Wollstadt et al., 2019). We reused the data from Hoebeke et al. (2023b) available at https://osf.io/k5dyf/. In order to conduct the information theory-based analyses, we first had to preprocess the data in R by testing for outliers and then imputing missing data using a Kalman filter implemented in the package "imputeTS" (Moritz & Bartz-Beielstein, 2017) because the analyses cannot address missing values. We also tested for stationarity using the Kwiatkowski–Phillips–Schmidt–Shin test (KPSS; $p > 0.05$ using a Bonferroni correction): all variables were stationary. Because some analyses are more easily conducted in R whereas the IDTxl package requires python, we used an R markdown file in RStudio to alternate between python and R and function calls to the JIDT toolkit and IDTxl python package. The code and data for these analyses can be found on the Open Science Framework repository:

https://osf.io/z7a2v/?view_only=99c0a994e1cf40c9939e8af85685f26d.

Defining the embedding size

The "embedding size" refers to the number of previous points in a time series that are considered in the calculation of transfer entropy. We relied on auto-mutual information as a heuristic to help us decide on a maximum lag parameter to best avoid the "false reverse inference due to inadequate embedding" which can happen when too few lags are included (see Vicente et al., 2011). Auto-mutual information (AMI; noted $I(X;X_{t-k})$) is the information shared between the current state of a variable and k past state, that is, the information we learn about a variable X from its value at k lags in the past. AMI is a symmetric measure and equals zero if the two values are independent. It can be viewed as a non-linear form of correlation. Hence, it is a useful metric to detect and quantify variable dependence, both linear and non-linear. It can be viewed as the information-theoretic equivalent of autocorrelation.

We first computed AMI for all variables using JIDT and the Kraskov (KSG) estimator, which is non-parametric and does not require binning continuous data or assuming gaussianity, to estimate how many time lags to include in the transfer entropy analysis. As AMI seems to plateau after 19-20 lags (see Figure 19), we used 19 lags as the max_lag setting of the transfer entropy analysis. We set the minimum lag parameter to zero as it is expected that psychological processes/symptoms share a lot of information within the same measurement window, especially considering that measurements are separated by about four hours throughout the day. By setting the minimum lag parameter to zero, we effectively consider 20 past states. As we have four measurements a day, 20 timepoints correspond to five days' worth of data. We also computed the transfer entropy analyses for four-, three-, two-, and one-day worth of data, and provide these results in supplemental material (see Figures S1-S4 in the Supplementary Material).

Figure 19. Auto Mutual Information

Note. exe_control = attention control, "When I wanted to deliberately concentrate on something, I was capable of ignoring environmental distractions (noise, notifications, visual distractors, ...)"); perseveration = "How much time did you spend thinking of one or more emotional experiences?"; negativity = "To what extent were your thoughts negative?"; criticism = "To what extent were your thoughts self-critical?"; replaying = "To what extend have you mentally replayed emotional experiences that you've had?"; brooding = "How much did you think about the causes and consequences of emotional experiences?".

Multivariate Transfer Entropy Analysis

We then used the IDTxl package to compute multivariate transfer entropy (MTE) using these parameters. IDTxl uses an iterative greedy algorithm proposed by Lizier & Rubinov (2012) and by Faes et al. (2011). This method allows us to construct an optimal set of source variables (predictors) for each target variable in a computationally efficient manner. It is "greedy" because it will iteratively include variables from a source's past by maximizing for a conditional mutual information criterion and it will only include a variable if it provides new information beyond the information already contained in its past states and the past states of other sources. This calculation constructs a set of parent sources for each target node.

We computed transfer entropy using the Kraskov (KGS) estimator and assessed statistical significance of links using the integrated permutation test in IDTxl (Novelli et al., 2019), with the default parameter of 500 permutations, alpha level set to 0.05, and the false discovery rate correction parameter set to true. We also computed active information storage (AIS) separately since the multivariate transfer entropy function internally computes active information storage but does not yet make this data available. By computing active information storage in addition to transfer entropy, it allows us to examine how much of the past of a variable is predictive of its next state.

We plotted the results using two different methods. First, we used the integrated plotting function of IDTxl. This method gives us one plot per target variable and shows which past states of the sources variables provide information about the parent variable while also showing which past states of the target provide information about its current state (see Figure 20). Second, we used the qgraph package in R (Epskamp et al., 2012) to create a network plot representing the omnibus transfer entropy values (i.e., total information provided by all the sources variables taken together) for all target variables, the aggregate transfer entropy values for all the past states of a source variable to a target variable, the active information storage values, and a visual representation of how many past states of a target variable are predictive of its current state using colored bars (see Figure 21). Both plots are complementary as one shows all the lagged associations with all variables whereas the other gives an overview of the relations between all variables and allows to visually examine the associations.

Lastly, we also made a correlation matrix between all six ESM variables and their value at the previous time point (see Supplementary material, Figure S5). As the MTE analysis does not indicate the nature of the associations, the correlations, although only accounting for linear effects, give us an idea of the general nature of the associations.

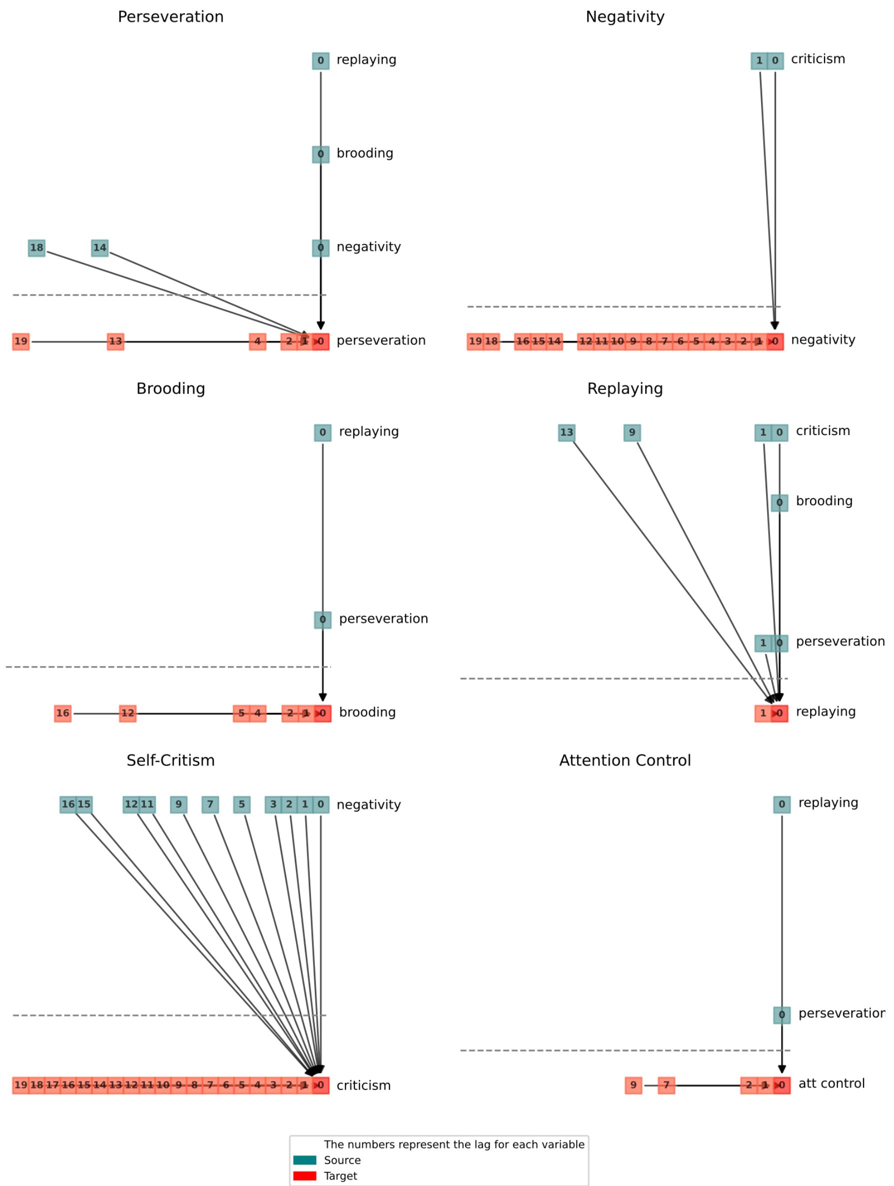
9.3 Results

We excluded one participant who had a variance and mean of zero on two items, and removed one outlier response with a response time of 289 minutes. A total of 2184 observations (39 participants) were included in the analysis.

Figure 20 shows the plot of the significant temporal dependencies between all the variables and their past states. Figure 21 shows the overall transfer entropy values between source variables and target variables (i.e., all information from significant lags are aggregated), the active information storage values, and the omnibus transfer entropy values (i.e. aggregated information provided by all linked source variables). First, **negativity** and **self-criticism** have the highest information storage. For both variables, almost all their past states provide significant new information on their current state. This indicates that past states of negativity and self-criticism are highly predictive of their future states. Additionally, these two features of rumination predict each other. Note that several lags of negativity predict self-criticism whereas only lag 0 criticism and lag 1 criticism predict negativity beyond the past states of negativity. Negativity and self-criticism also predict perseveration and replaying, respectively. Second, **brooding**, **perseveration**, and **replaying** have lower information storage and only a few significant lagged dependencies (cf., Figure 21). This suggests that only a few past states are predictive of their future states. However, they are all interrelated and provide information on each other, seemingly forming a cluster. Moreover, they stand out by having the highest omnibus transfer entropy values, which means that they are the most strongly predicted variables in this network.

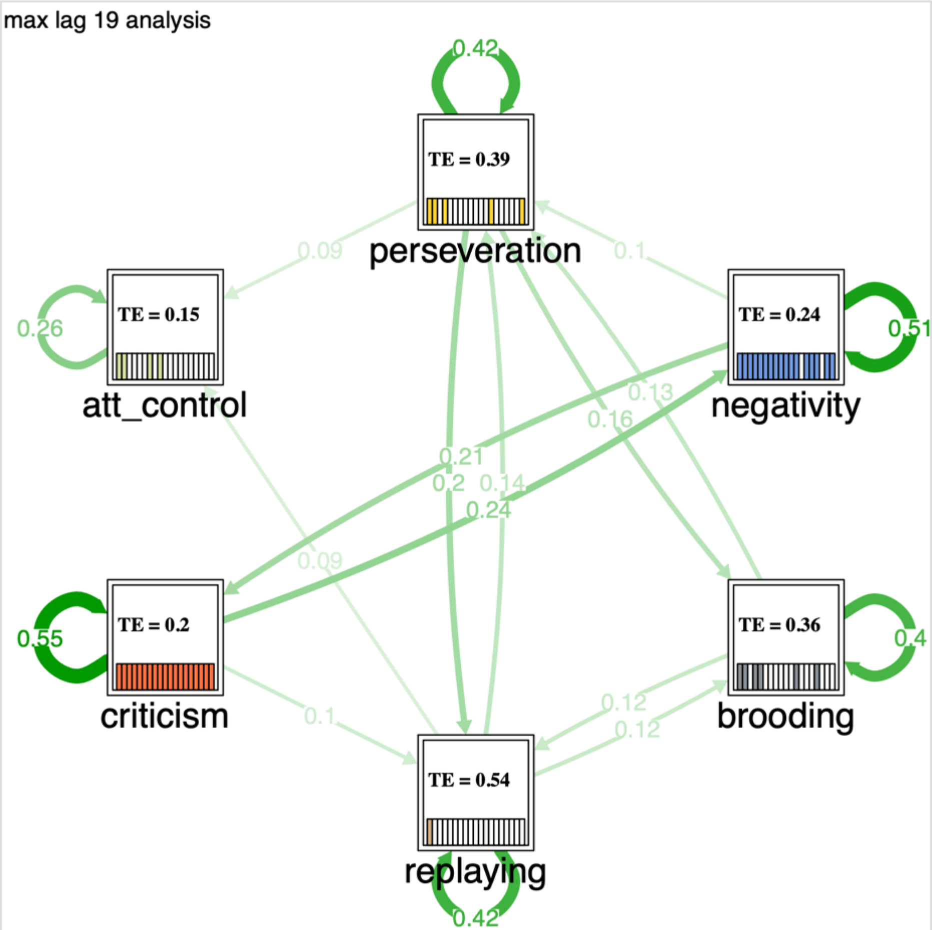
Finally, **attention control** has the lowest omnibus transfer entropy value. This indicates that it was the least influenced by the other variables in the system. It is only predicted by perseveration and replaying within the same timeframe.

Figure 20. Target variable parents based on mTE



Note. These plots allow to visualize the lags of source variable that significantly provide directed information (i.e., as reflected in the arrows) about the target variable. The target variables are in red whereas the source variables are in blue. The number in the squares represent the lag number.

Figure 21. Network visualization of the multivariate transfer entropy results



Note. TE = omnibus transfer entropy; Edge weight = transfer entropy from source to target; Self loop = active information storage value. The colored bars indicate which past values of the target contribute to the active information storage value, starting with the left one as lag 1.
"Max 19 lag analysis" indicates that these are the results of the multivariate transfer entropy accounting for 19 past lags.

9.4 Discussion

This study aimed to use, for the first time, multivariate transfer entropy (mTE) and active information storage (AIS) to analyze intensive longitudinal, self-reported psychological data. By reanalyzing data from Hoebeke et al. (2023), our objective was to unravel the dynamic interplay among five distinct features of rumination and attention control. The findings offer new perspectives on the associations between attention control and features of rumination, the interrelationships among the features of rumination, and the benefits and limitations of using mTE and AIS in psychological research.

In exploring the relationship between attention control and rumination, our findings suggest that features of rumination serve as predictors for attention control, but not vice versa. This observation aligns with the resource depletion hypothesis, which posits that rumination consumes cognitive resources, leading to diminished attention control, as supported by prior research (e.g., Connolly et al., 2014; Curci et al., 2013). However, it is noteworthy that our results diverge somewhat from those derived from the same dataset using a multilevel autoregressive model (mlVAR) by Hoebeke et al. (2023). In that study, the negative content of thoughts was found to directly predict decreased attention control both concurrently and in subsequent states. In contrast, the multivariate transfer entropy analysis suggests an alternate pathway: both negativity and self-criticism influence perseveration and replaying, which in turn affect attention control. This divergence is significant as it highlights the different insights offered by various analytical approaches: while mlVAR emphasizes direct, lagged associations, our transfer entropy analysis suggests a more immediate, within-time point association, without evident lagged effects. This difference underscores the necessity of employing multiple analytical perspectives to fully grasp the complex dynamics of psychological processes.

The rumination features of perseveration and replaying could reflect the consumption of cognitive resources by rumination processes. Perseveration, in this context, represents the duration of ruminative thought, while replaying involves the mental revisiting of emotional experiences. Despite both the mlVAR (Hoebeke et al., 2023) and the transfer entropy analyses aligning with the resource depletion theory, the latter provides a more nuanced understanding. It suggests that the impact on attention control is less about the negative content of thoughts and more about the act of rumination itself, such as the continuous replaying and persistent thinking about distressing events. These ruminative activities monopolize attentional resources, detracting from their availability for other cognitive tasks and leading to a concurrent reduction in attention control. This interpretation is further supported by the relatively low omnibus transfer entropy value for attention control, indicating that while the effect exists, it may be modest in its influence.

Beyond these insights about the interplay between attention control and rumination, our findings also provide insights into rumination. For instance, the analysis revealed distinct patterns among the rumination features, forming two discernible clusters. The first cluster encompasses content-related aspects of rumination, specifically negativity and self-criticism. These aspects are marked by high active information storage and several significant past lags, and they predicted each other. These findings illustrate how these features can reinforce each other: a person prone to self-criticism will generally have more negative thoughts, and one that has more negative thoughts will likely be more self-critical. Conversely, in the second cluster consisting of process-related features (i.e., perseveration, replaying, and brooding), the features displayed lower active information storage but notably higher omnibus TE values. This implies that these process-oriented features are more strongly influenced by other variables within the network. Importantly, the content-related features exerted a predictive influence on the process-related features, establishing a directional flow of influence within the rumination network.

These findings suggest a causal relationship, where the content-related features of rumination may influence the process-related features. Specifically, the extent to which a person's thoughts are negative and self-critical, observed both concurrently and in previous states, appears to significantly predict their levels of perseveration and replaying. These two process-oriented features, in turn, demonstrate a bidirectional relationship with brooding, indicating a complex interplay within the rumination network. Interestingly, the prediction of replaying by multiple past lags of criticism (see Figure 20) could imply that high replaying scores reflect the reiteration of previous events that drew self-criticism from the participant. This insight underscores the role of self-criticism in perpetuating a cycle of rumination, particularly in the context of re-examining past emotional experiences.

These findings prompt a reevaluation of traditional views which emphasize the repetitive nature of rumination and similar thought processes as their defining characteristic (Ehring & Watkins, 2008). Instead, our results align more closely with the Goal-Progress Theory (Martin & Tesser, 1989), which posits that rumination arises and persists as a response to perceived unsatisfactory progress towards a goal or a discrepancy between reality and a goal until their focus shifts elsewhere. From this perspective, the features of negativity and self-criticism in our study can be seen as markers of these perceived goal discrepancies. In contrast, perseveration, replaying, and brooding could be understood as consequences of an ineffective emotion regulation strategy, one that raises awareness of these goal discrepancies without necessarily resolving them. This is particularly evident in the context of rumination, which often fixates on past, unchangeable situations. However, it could also be relevant for other types of repetitive thought processes such as worrying. For instance, worry about future events such as academic exams might stem from an awareness of inadequate preparation, creating a perceived threat to the goal of success. Consequently, the central element shared by thought patterns such as worrying and rumination may not be their repetitive nature, but their origin in perceived discrepancies related to goal achievement.

The active information storage (AIS) analyses offer intriguing insights into the stability of features of rumination, suggesting that certain features may be more stable and less context-dependent than other features. Notably, negativity and self-criticism were marked by high AIS and exhibited several significant past lags, meaning their past states significantly help predict their present state. This pattern may suggest that these features represent more stable, trait-like characteristics, potentially shaped by a combination of external and internal factors. For instance, recurrent exposure to adverse situations (external factor) or a predisposition towards a negative interpretation bias (internal factor) could perpetuate negative thought patterns (Watkins & Roberts, 2020). This resonates with earlier psychological theories that conceptualized negative affectivity as a general disposition (Watson & Clark, 1984), and aligns with research linking such dispositions to rumination. For example, addressing interpretation biases has been shown to effectively reduce worry, rumination, and depression (Hirsch et al., 2018; Hirsch et al., 2020). Similarly, self-criticism, often viewed as a personality trait (Schance, 2013; Zuroff, 2016), also appears to reflect a more ingrained aspect of an individual's psychological makeup. Thus, the AIS findings appear to have captured the dispositional nature of these two features of rumination in daily life.

In stark contrast, the process-related features of rumination and attention control exhibited lower active information storage and fewer significant past states contributing new information. This suggests that these aspects may be more influenced by the immediate context and are possibly less stable over time. However, it is important to note that all variables in our study displayed some significant past lags. This indicates that their future states can be better predicted by considering not just their immediate past state but also a few preceding states. For instance, accurately predicting an individual's current level of attention control might benefit from knowing their attention control in preceding periods (e.g., their attention control 4 hours prior but also days prior). The significance of these past states may be attributed to transient factors impacting attention control, such as sleep deficiency, which has been documented to affect attention control in subsequent days (Whitney et al., 2017).

The insights lead to a broader consideration of the benefits and limitations inherent in multivariate transfer entropy (MTE) and active information storage (AIS). These methodologies offer substantial advantages for dissecting complex multivariate time series data. MTE and AIS, as non-parametric analyses, adeptly capture a range of associations—both linear and nonlinear—as well as lagged and cumulative effects, while also pruning redundancies and accounting for synergies. This robustness is particularly advantageous in exploratory analyses of multivariate time series, helping to differentiate potential causal drivers (like self-criticism and negativity) from their resultant effects (such as perseveration and replaying). Furthermore, MTE appears to have unveiled the dynamics between rumination features and attention control more effectively than the mlVAR analysis. This enhanced capability likely stems from MTE and AIS's consideration of multiple past lags and proficiency in detecting nonlinear associations, in contrast to the focus of mlVAR on single-lag, linear relationships.

However, it is crucial to acknowledge the limitations associated with MTE and AIS methodologies. A key challenge lies in selecting an appropriate embedding size—the number of past lags to consider—which remains an area for further exploration. In our study, we based our approach on auto-mutual information and the auto-embedding feature in IDTxl. Analyzing fewer lags than those suggested by the auto-mutual information cut-off revealed significant fluctuations in inferred associations, as detailed in our Supplementary Material. Moreover, MTE analyses are both time and data intensive. They necessitate exhaustive testing across numerous potential lags and variables. Consequently, sensitivity analyses, while helpful in addressing certain limitations, demand substantial computational resources. Furthermore, requirements such as data stationarity, equidistant measurement intervals, and the need for datasets without missing values can present additional challenges in applying these methods.

Nevertheless, there are potential solutions to address some of the limitations inherent in MTE and AIS. For example, while achieving stationarity in longer time series can be challenging, there are extensions of transfer entropy that cater to non-stationary time series (Papana et al., 2016). In cases where equidistant measurement spacing is not feasible, time-varying transfer entropy offers a viable alternative (Shorten, 2021). Furthermore, interpreting directed links in these analyses can be intricate, as a source being identified as a parent of a target does not always equate to it providing unique, directed pairwise information, because a directed link in an effective network implies that a source variable is a parent of a target in conjunction with the other parent variables of that target (Bossomaier et al 2016). This complexity underscores the need for further analyses. Multivariate partial information decomposition (PID), as proposed by Kolchinsky (2022) and Lizier (2018), can aid in disentangling the synergistic, redundant, and unique contributions among sets of source variables to a target. Additionally, factors like time of day and the directional nature of associations, which are not directly accounted for in MTE and AIS analyses, necessitate supplementary confirmatory analyses. Thus, while MTE and AIS offer distinct advantages over traditional frequentist methods like mlVAR, they are not panaceas. A holistic approach, employing these techniques alongside other analytical methods, is crucial for a thorough understanding of the temporal dynamics in psychological time-series data.

In addition to the limitations inherent to MTE, this study faces its own specific constraints. Firstly, the total number of observations, amounting to 2184, could be perceived as insufficient for such a data-intensive analysis. We partly addressed this limitation through significance testing via a permutation test. Nevertheless, future research would benefit from a larger dataset, particularly when planning to incorporate more variables into MTE analyses. Secondly, employing transfer entropy analysis entails certain assumptions and prerequisites, including the need for equidistant measurements in time and complete datasets without missing values. However, our study worked with data that did not adhere strictly to these requirements, as it involved both non-equidistant time measurements and imputed missing values. These aspects of our methodology could potentially impact the robustness of our findings. Consequently, future studies might explore alternative analytical methods that can accommodate variations in the timing of measurements and handle data without necessitating equidistant intervals, thus enhancing the reliability and applicability of the results.

9.5 Conclusion

In conclusion, our study has provided meaningful insights into the intricate dynamics between attention control and five features of rumination, utilizing multivariate transfer entropy (MTE) and active information storage (AIS) for analysis. We discovered that features like negativity and self-criticism likely represent stable dispositions, while others such as replaying, brooding, and perseveration, along with attention control, appear to be more transient and influenced by the immediate context. Our analysis suggests a cascading influence where negativity and self-criticism lead to perseveration and replaying, which subsequently impacts attention control, supporting the resource depletion hypothesis of rumination. Lastly, we believe that these results also demonstrate the usefulness of MTE and AIS in revealing the nuanced interdependencies within multivariate time-series data and therefore position itself as an alternative to other methods such as structural equation modeling and multilevel vector autoregressive models.

Chapter 10.

Predicting depression and anxiety from the temporal features of rumination: an affective dynamic approach

Background. Rumination, characterized by repetitive negative thoughts about one's emotions and experiences, is a transdiagnostic process involved in various emotional disorders. While statistical tools from affective dynamics have been largely applied to elucidate the temporal dynamics of affect, it has seldom been used in rumination research. In this study, we aimed to examine the predictive value of moment-to-moment variability and inertia of rumination features, comparing them against person-level means, standard deviations, and trait rumination.

Methods. Forty participants answered five rumination items four times daily over two weeks, with self-report questionnaires at the end. From these intensive time-series data, we computed inertia (using a multilevel vector autoregressive model) and moment-to-moment variability per participant and then analyzed the data using regression models to predict depression and anxiety symptomatology.

Results. Rumination metrics derived from the time-series data better predicted depression and anxiety than trait rumination alone. Yet, the best-performing models included both these temporal measures and trait rumination, accounting for 67.2% of depression variance and 51.1% of anxiety. Only the inertia of one specific feature of rumination, that is, the negativity of thoughts, had added predictive value for depression, after controlling for person-level means, standard deviations, and trait rumination. Importantly, the moment-to-moment variability of rumination features did not add any predictive value, corroborating previous research on affective dynamics. In addition to inertia of negativity, the person-level means of content features of rumination, trait rumination, and self-criticism variability positively predicted depression, whereas negativity variability negatively predicted depression. In contrast, only the person-level mean of the content features and trait rumination predicted anxiety.

Conclusion. Overall, this study underscores the value of considering the dynamic nature of rumination and the combined insights trait rumination and temporal measures of rumination features can offer in understanding depression and anxiety symptomatology.

Reference
Hoebeke, Y., & Heeren, A. (submitted). Predicting depression and anxiety from the temporal features of rumination: an affective dynamic approach.

10.1 Introduction

Individuals inevitably encounter a diverse range of emotions throughout life. To best capture these emotional experiences, researchers have increasingly focused on measuring affect, emotions, and other psychological processes in daily life using Experience Sampling Methods (ESM; Hektner et al., 2007). These studies vary in frequency of measurements and duration. While some studies have focused on daily measurements, others have included measurements every few hours, or measurements contingent on specific triggers and events. Therefore, in ESM studies, measurements are typically separated by minutes or hours, rather than weeks, months, or years, providing a more nuanced, dynamic understanding of psychological processes. This shift towards shorter timeframes in data collection is part of a larger movement in psychological research towards capturing the dynamics of psychological processes. This paradigm shift has given rise to several burgeoning fields, such as affective dynamics (Waugh & Kuppens, 2021).

Central to affective dynamics research is the notion that it is not just the mere presence or intensity of emotions, but their fluctuations, that imbue our lives with meaning (Kuppens, Oravecz, et al., 2010; Scherer, 2009). Within affective dynamics research, scholars are particularly interested in concepts such as emotional inertia—how strongly a variable predicts itself from one moment to the next—and moment-to-moment emotional variability, also referred to as instability, drawing parallels with practices in physiology. For instance, practitioners may not just consider the average heart rate but also the fluctuations in intervals between heartbeats, namely heart rate variability, which is now largely viewed as a better predictor of health than the average heart rate per se (Mccraty & Shaffer, 2015). In the same vein, a growing body of literature suggests the moment-to-moment fluctuations in intensity of an emotional state (and not the fluctuations between distinct types of emotional states) are associated with mental health. Especially, both high inertia (that is, an absence of temporal variability from one time point to the next) and moment-to-moment variability (that is, strong fluctuations from one time point to the next) of affect have been associated with mental health (for a meta-analysis, see Houben et al., 2015).

However, emotions are not the only processes subject to temporal fluctuations in daily life; our thoughts, like intrusive thoughts and worry, are dynamic, too. They can shift in response to affective experiences, shape these experiences, or even fluctuate independently of changes in affective experiences, as seen during mind-wandering. Consequently, several researchers have started to apply the computational tools from the field of affective dynamics to thoughts in daily life.

Take, for example, the concept of inertia, which goes beyond affect and has been applied to rumination. This latter involves repetitive negative thoughts about the content, causes, and consequences of emotions and events without active problem-solving (Nolen-Hoeksema et al., 2008). In ESM studies measuring rumination daily in participants with depression (Bean et al., 2020) and nonclinical participants' (Bean et al., 2021), temporal fluctuations of rumination were characterized by inertia (i.e., strong pattern of autoregression and temporal persistence from one day to the next). Moreover, depression severity moderated inertia intensity, with participants with more severe depressive symptoms showing higher levels of ruminative inertia (Bean et al., 2020). Likewise, rumination and negative affect, measured several times a day, predicted each other from one time point to the next and were both characterized by inertia, in both clinical and nonclinical samples (Blanke et al., 2021; Hjartarson et al., 2021, 2022b). Taken together, this set of findings suggest that rumination's inertia might constitute a risk factor for mental disorders, and especially depression.

Yet, although the inertia of rumination (i.e., its propensity to persist from one time point to the next; Kuppens, Allen, et al., 2010) has been largely explored, the moment-to-moment variability of rumination (i.e., the differences in intensities from one time point to the next; Kuppens, Allen, et al., 2010) have seldom been considered, and to our best knowledge, never been explored, neither its potential link with depression and anxiety symptomatology. Although one may wonder whether these two affective dynamic metrics are like the two faces of a same coin, it is important to note that they are not. In a large a reanalysis of time-series data of affect from 15 studies, there was no significant correlation between inertia and RMSSD (Dejonckheere et al., 2019). Hence, it is possible for instance for affect to be both relatively stable (high inertia) and show moment-to-moment variability (high RMSSD) within certain bounds, or to be unstable (low inertia) but with less moment-to-moment variability (low RMSSD).

Moreover, despite the growing interest in affective dynamic approach to rumination, two key questions remain unanswered. The first question pertains to whether inertia and moment-to-moment variability applied to rumination better predict depression and anxiety symptomatology than a mere person-level means of the temporal data or than the trait measurement resulting from one time point assessment of rumination. For instance, in the case of emotional states, dynamic metrics did not significantly predict life satisfaction, depression, and borderline symptoms once the mean and standard deviation were accounted for (Dejonckheere et al., 2019). Yet, uncertainty remains regarding rumination.

In the context of rumination, studies did not probe whether ESM measures of rumination are more potent predictors of psychopathology than equivalent trait measures of rumination. However, one study by Hann et al. (2023) has examined a related question. Over a 28-day ESM study, the authors examined whether state rumination (measured eight times a day) and person-level means of state rumination predicted momentary negative affect more accurately than trait rumination at baseline, using mixed models. They found that state rumination was a stronger predictor of state affect than trait rumination. Conversely, it remains to be determined whether trait rumination might more strongly predict trait measures of psychopathology compared to state rumination.

A second limitation concerns the conceptualization of rumination in previous research on the affective-dynamic approach to rumination. In this research, rumination was usually reduced to a single item or single sum-score, conceived as a cohesive and unified phenomenon. Yet rumination is fundamentally a multifaceted construct. For example, Nolen-Hoeksema's (1991) classic definition includes perseveration, brooding, replaying, negativity, and self-critical focus. As such, applying the tools from the affective dynamic approach to rumination without considering its multifaceted nature may oversimplify the story, especially since it is easy to generate examples of how these hallmark features may differ in their temporal variations. For example, one might easily expect inertia to be higher in perseveration than in other facets. Moreover, previous research already indicated that the features of rumination have distinct associations among them and that the negative valence of thoughts seems to drive the other features of rumination (Hoebeke et al., 2023).

Therefore, in this project, we had two main goals. First, we wanted to examine the inertia and moment-to-moment variability of five key features of rumination. Second, we aimed at testing whether the inertia and moment-to-moment variability of rumination's features better predict depression and anxiety symptoms than a mere person-level means (across the temporal data) or trait measurement resulting from one time point assessment of rumination. To this end, we reanalyzed data from Hoebeke et al. (2023a), which includes intensive time-series data on the five hallmark features of rumination were assessed four times a day for 14 days, along with trait measures of depression, anxiety, and rumination.

10.2 Method

10.2.1 Open Science Practices and Data Sharing

De-identified data, R script, and other supplemental materials have been made publicly available via the Open Science Framework at https://osf.io/dj7ug/.

All participants provided written informed consent. The project received the approval of the UCLouvain biomedical review board (REF# 2020/057). All participants provided written informed consent. Participants received 50€ for participating in the entire study.

10.2.2 Participants

The data was gathered from 40 French-speaking Belgian participants, aged 18–26 years (*M* = 21.2, *SD* = 2.03, 77.5% female), from the general community via social media. Participants had relatively low scores for trait depressive, anxious symptomatology, and trait rumination (see Table S1 in Supplementary Material).

10.2.3 Measures

ESM rumination measure. This measure of state rumination consists of five items, each assessing a distinct feature of rumination: perseveration (i.e., "How much time did you spend thinking about one or more emotional experiences?"), negativity (i.e., "To what extent were your thoughts negative?"), criticism (i.e., "To what extent were your thoughts self-critical?"), replaying (i.e., "To what extent have you mentally replayed emotional experiences that you've had?"), and brooding (i.e., "How much did you think about the causes and consequences of emotional experiences?"). The development procedure for these items and their psychometric properties are detailed in Hoebeke et al. (2022).

Depressive and anxious symptomatology. We used the Beck Depression Inventory (BDI-II; Beck et al., 1996) and the Generalized Anxiety Disorder Scale (GAD-7; Spitzer et al., 2006) to measure depressive symptoms and anxiety symptoms. We administered the French versions of these scales.

Trait rumination. We used the Ruminative Response Scale (RRS; Treynor et al., 2003) to measure the tendency to ruminate. We only use the brooding and reflection subscales for the analyses, each made of five items of the 22 items of the RRS (RRS-10; Treynor et al., 2003).

10.2.4 Study Protocol

We used a time-contingent sampling scheme with fixed intervals: participants received text messages four times a day (at 09:00, 13:00, 17:00, and 21:00) containing a link to the survey. The ESM survey consisted of the five items measuring five features of rumination. We assessed them using a slider scale ranging from 0 (not at all) to 100 (absolutely). Upon concluding the two-week ESM protocol, participants completed the RRS, BDI-II, and GAD-7.

10.2.5 Data Analysis

Data were analyzed using R, version 4.2.2 (R Core Team, 2022). One participant was removed from the analyses as they had zero variance on two ESM items. We calculated the descriptive statistics of the trait measures and ESM measures (see Supplementary Material, Table S1). We also created a correlation matrix (see Figure 22) and made boxplots of the inertia and variability of all rumination features to visually compare their values (see Supplementary Material, Figure S1).

Temporal Dynamics Indices

Following Dejonckheere et al. (2019), we chose to focus on two types of statistical indices used in the affective dynamics' literature: moment-to-moment variability (RMSSD; root of the mean square of the sum of the successive differences) and inertia. Moment-to-moment variability is computed using the same method as heart rate variability (using RMSSD). However, in psychological sciences, researchers typically use differences in intensities from one moment to the next instead of time differences between heartbeats. Inertia refers to the propensity of a state to persist from one moment to the next (Kuppens, Allen, et al., 2010), which is measured by calculating the autocorrelation of a process over a specific period.

We computed person-level RMSSD and person-level inertia values for each ESM item. The results of a multilevel vector autoregressive model (mlVAR; Epskamp, Waldorp, et al., 2018) were used to derive person-level inertia values by extracting the random intercept for each participant (as discussed in Koval et al., 2021). This approach ensures that only the autoregressive effect of a variable, after accounting for all other temporal associations, is considered. Note that the mlVAR model does not consider the association between the last measurement of the day and the first measurement of the next day. Hence, we calculated the RMSSD for each participant in the same way, by adding empty rows between days so that only the variability between successive measurements within a day is considered.

Regression Analyses

Before conducting the regression analyses, we combined strongly correlated variables into composite variables. We did this to avoid problems of collinearity and to reduce the complexity of the models. We combined the following variables with high correlation: (1) perseveration, brooding, and replaying person-level means (r = 0.89–0.95, $p < .001$); (2) negativity and criticism person-level means (r = 0.79, $p < .001$); (3) replaying, brooding, and perseveration RMSSDs (r = 0.73–0.79, $p < .001$); and (4) SDs of replaying, brooding, and perseveration person-level SDs (r = 0.81–0.85, $p < .001$). Notably, we had to create three composite variables for the 'process' related features of rumination. Indeed, brooding, replaying, and perseveration all refer to a process-like aspect of rumination, whereas negativity and criticism refer to the content of thoughts. Moreover, other correlations were also strong, mainly between the RMSSD and the respective SDs of variables.

We conducted hierarchical regressions by fitting five different models for depression and anxiety with the following predictors: (1) only ESM means; (2) ESM means and SDs; (3) ESM means, SDs, and inertia; (4) ESM means and inertia; (5) ESM means, SDs, inertia, and RMSSDs. To address our third objective, we also computed two additional models: one with trait rumination added as a predictor with the other variables and one with trait rumination alone. We checked the assumptions for each model and we especially checked for multicollinearity.

Sensitivity analyses

Given the considerable number of predictors relative to our sample size, we chose to perform a sensitivity analysis. To this end, we conducted variable selection, which is the process of "excluding irrelevant variables from a multiple regression model" (Sohil et al., 2022, p. 234). It allows for better model interpretability and model accuracy as it can lead to a less complex model by removing unnecessary variables by constraining or shrinking the estimated coefficients. We decided to use subset selection and lasso regression with cross-validation. Subset selection consists of testing all possible combinations of predictor variables and then selecting the best subset of predictors according to a statistical criterion (A. Miller, 2002). Lasso regression shrinks the regression coefficients of unnecessary predictors to exactly zero. For the cross-validation, we used Leave-One-Out Cross-Validation (LOOCV). In LOOCV, each observation is left out once and the model is trained on the remaining data, and then validated on the left-out observation, allowing for an unbiased assessment using the entire dataset. The best model is the model with the overall lowest prediction error.

10.3 Results

10.3.1 Descriptive statistics

The descriptive statistics for all variables are provided in the supplementary material in Table S1, while Figure 22 depicts the correlation matrix. We observe that the RMSSD composite variable of process features is strongly positively correlated with its standard deviation (r = 0.86,

$p < .001$). The same holds for the RMSSD and SD of negativity ($r = 0.83$, $p < .001$) and the RMSSD and SD of criticism ($r = 0.91$, $p < .001$). We also observe that the inertia of perseveration is negatively correlated with the RMSSD of process features ($r = 0.69$, $p < .001$) and their SD ($r = -0.50$, $p < .01$). Notably, among all inertia, RMSSD, and SD indices, only the SD of criticism significantly correlated with BDI-II scores ($r = 0.42$, $p < .01$). Moreover, none of the inertia values are correlated with the person-level means or the trait questionnaires. Finally, RRS-10 scores are only negatively correlated with the mean of the process features ($r = 0.55$, $p < .001$) and positively correlated with brooding SD ($r = 0.34$, $p < .05$).

Figure 22. Correlation matrix

	PL means process features	PL means content features	RMSSD process features	PL SD process features	RMSSD Negativity	SD Negativity	RMSSD Criticism	SD Criticism	Inertia - negativity	Inertia - criticism	Inertia - perseveration	Inertia - brooding	Inertia - replaying	RRS-10	BDI-II	GAD-7
PL means process features	1.00	***												***	***	**
PL means content features	0.58	1.00				*									**	***
RMSSD process features	0.24	0.00	1.00	***	***	***	***	**		*	***					
PL SD process features	0.22	0.07	0.86	1.00	***	***	***	**		*	**					
RMSSD Negativity	0.30	0.30	0.69	0.64	1.00	***	***	***	*		**					
SD Negativity	0.24	0.37	0.59	0.75	0.83	1.00	***	***			*					
RMSSD Criticism	0.19	0.07	0.58	0.58	0.68	0.58	1.00	***								
SD Criticism	0.26	0.19	0.45	0.49	0.60	0.57	0.91	1.00							**	
Inertia - negativity	-0.18	0.14	-0.19	0.05	-0.35	0.11	-0.22	-0.16	1.00							
Inertia - criticism	0.06	0.18	-0.35	-0.34	-0.23	-0.21	-0.15	0.17	-0.13	1.00						
Inertia - perseveration	-0.08	0.18	-0.69	-0.50	-0.41	-0.34	-0.28	-0.18	0.20	0.26	1.00	*				
Inertia - brooding	0.05	-0.02	0.07	0.18	0.10	0.17	-0.07	-0.10	-0.12	-0.12	-0.34	1.00				
Inertia - replaying	0.06	-0.19	0.20	0.03	0.03	-0.09	0.07	0.05	-0.13	-0.14	-0.26	-0.03	1.00			
RRS-10	0.55	0.18	0.31	0.27	0.17	0.19	0.02	0.02	-0.02	-0.25	-0.31	0.26	0.24	1.00	***	**
BDI-II	0.62	0.50	0.21	0.24	0.23	0.27	0.28	0.42	0.15	0.12	-0.07	-0.05	0.13	0.60	1.00	***
GAD-7	0.44	0.58	0.04	0.09	0.18	0.28	-0.02	0.06	0.21	-0.05	-0.05	0.29	-0.04	0.50	0.59	1.00

Note. PL means process features = composite variable of the person-level means of brooding, perseveration, and replaying; PL means content features = composite variable of the person-level means of negativity and criticism; RMSSD process features = composite variable of the RMSSD of brooding, perseveration, and replaying; PL SD process features = composite variable of the SD of brooding, perseveration, and replaying; BDI-II = Beck Depression Inventory; GAD-7 = Generalized Anxiety Disorder scale; RRS-10 = Ruminative Response Scale with 10 items.

Table 12. Hierarchical Regression Models Predicting Depression Symptoms

	Trait Only			ESM means			ESM means & SD			ESM means, SD, & inertia			ESM means & inertia			Trait and ESM variables		
Predictors	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***
Intercept	0.00	1.83	0.076	0.00	-0.09	0.930	-0.00	-1.17	0.251	-0.00	-1.61	0.118	-0.00	-1.38	0.178	-0.00	-2.26	**0.032**
Trait rumination	0.60	4.52	**<0.001**													0.54	3.87	**0.001**
PL means process features				0.49	3.11	**0.004**	0.39	2.36	**0.024**	0.47	2.75	**0.010**	0.54	3.20	**0.003**	0.11	0.67	0.507
PL means content features				0.21	1.35	0.185	0.28	1.56	0.129	0.22	1.12	0.271	0.17	0.98	0.336	0.29	1.84	0.077
PL SD process features							0.14	0.64	0.524	0.05	0.23	0.819				0.05	0.27	0.788
Negativity SD							-0.21	-0.89	0.381	-0.23	-0.93	0.361				-0.25	-1.27	0.216
Criticism SD							0.32	2.07	**0.047**	0.38	2.14	**0.041**				0.45	3.05	**0.005**
Inertia – perseveration										-0.08	-0.52	0.605	-0.13	-0.87	0.389	-0.01	-0.08	0.933
Inertia – negativity										0.33	2.33	**0.027**	0.28	1.97	0.057	0.25	2.12	**0.043**
Inertia – brooding										0.02	0.15	0.885	-0.06	-0.45	0.659	-0.07	-0.62	0.538
Inertia – replaying										0.13	0.97	0.340	0.15	1.12	0.273	0.04	0.36	0.719
Inertia – criticism										0.04	0.30	0.768	0.14	1.05	0.301	0.12	0.94	0.355
R^2 / R^2 adjusted	0.356 / 0.339			0.409 / 0.376			0.489 / 0.412			0.587 / 0.439			0.508 / 0.397			0.734 / 0.626		
	$F(1, 37) = 20.47$, $p < .001$			$F(2, 36) = 12.44$, $p < .001$			$F(5, 33) = 6.325$, $p < .001$			$F(10, 28) = 3.974$, $p = .001$			$F(7, 31) = 4.751$, $p = .001$			$F(11, 27) = 6.771$, $p < .001$		

Note. PL means process features = composite variable of the person-level means of brooding, perseveration, and replaying; PL means content features = composite variable of the person-level means of negativity and criticism; PL SD process features = composite variable of the SD of brooding, perseveration, and replaying.

Table 13. Hierarchical Regression Models Predicting Anxiety Symptoms

Predictors	Trait Only			ESM means			ESM means & SD			ESM means, SD, & inertia			ESM means & inertia			Trait and ESM variables		
	std. Beta	***t***	***p***	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***
Intercept	-0.00	2.04	**0.049**	-0.00	0.41	0.687	-0.00	0.22	0.825	-0.00	0.07	0.948	-0.00	-0.87	0.391	-0.00	-0.10	0.923
Trait rumination	0.50	3.47	**0.001**													0.39	2.22	**0.035**
PL means process features				0.16	0.96	0.342	0.21	1.13	0.265	0.23	1.21	0.237	0.19	1.11	0.277	-0.03	-0.15	0.881
PL means content features				0.49	2.97	**0.005**	0.42	2.09	**0.044**	0.45	2.14	**0.041**	0.47	2.67	**0.012**	0.51	2.54	**0.017**
PL SD process features							-0.07	-0.31	0.760	-0.22	-0.88	0.386				-0.22	-0.95	0.352
Negativity SD							0.21	0.82	0.420	0.04	0.15	0.879				0.02	0.09	0.930
Criticism SD							-0.15	-0.91	0.371	0.07	0.36	0.724				0.12	0.64	0.529
Inertia - perseveration										-0.10	-0.57	0.577	-0.03	-0.20	0.839	-0.05	-0.28	0.780
Inertia - negativity										0.25	1.61	0.119	0.21	1.50	0.143	0.19	1.30	0.205
Inertia - brooding										0.30	2.04	0.051	0.29	2.13	**0.042**	0.24	1.67	0.107
Inertia - replaying										0.04	0.25	0.803	0.06	0.41	0.685	-0.03	-0.20	0.846
Inertia - criticism										-0.12	-0.72	0.477	-0.06	-0.45	0.656	-0.07	-0.43	0.673
R^2 / R^2 adjusted	0.246 / 0.225			0.356 / 0.320			0.377 / 0.282			0.507 / 0.330			0.490 / 0.374			0.583 / 0.413		
	$F(1, 37) = 12.06$, $p = .001$			$F(2, 36) = 9.929$, $p < .001$			$F(5, 33) = 3.992$, $p = .006$			$F(10, 28) = 2.874$, $p = .013$			$F(7, 31) = 4.25$, $p = .002$			$F(11, 27) = 3.431$, $p = .004$		

Note. PL means process features = composite variable of the person-level means of brooding, perseveration, and replaying; PL means content features = composite variable of the person-level means of negativity and criticism; PL SD process features = composite variable of the SD of brooding, perseveration, and replaying.

10.3.2 Hierarchical regression models

Table 12 and Table 13 present the regression model results for depression and anxiety, respectively. Notably, adding the RMSSDs values to the regression models caused collinearity: the RMSSDs of all variables were significantly correlated with the respective SDs of each variable (r = 0.83–91, $p < .001$). Moreover, they did not add any predictive value. We therefore do not report the model with RMSSDs.

Predictive value of ESM metrics

Depression

The full ESM model with person-level means, SDs, and inertia values explains 43.9% of the variance of depression, $F(10, 28) = 3.974$, $p = .001$. Inertia values explain an additional 3.7% variance compared to means and SDs, and 2.1% more variance compared to means only. In the full ESM model, only person-level means of the process features of rumination (i.e., replaying, perseveration, and brooding), the SD of self-criticism, and the inertia of negativity predict depressive symptoms.

Anxiety

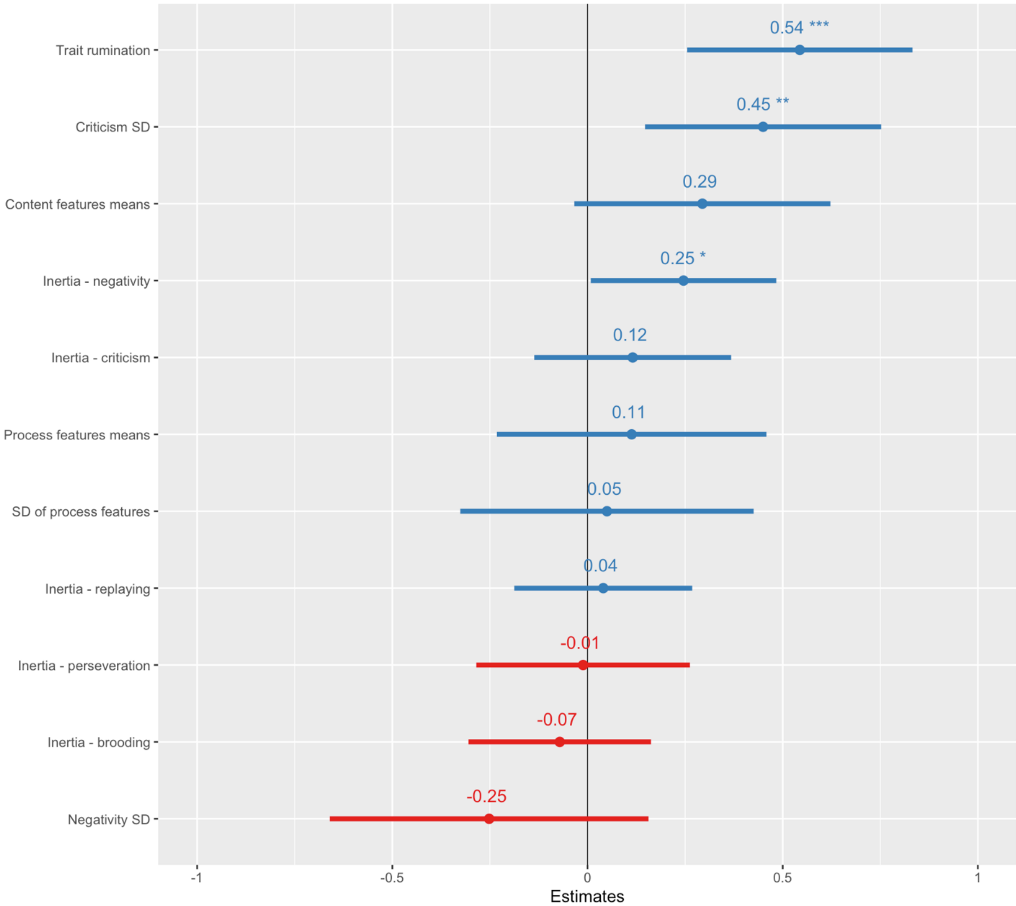
The full ESM model with person-level means, SDs, and inertia values explains 33% of the variance of anxiety, $F(10, 28) = 2.874$, $p = .013$. Inertia values explain an additional 4.8% variance compared to means and SDs, and 1% more variance compared to means only. A caveat however is that SDs seem to reduce the explained variance, with the model with SD explaining 3.8% variance less than the model without SDs. Hence, comparing the predictive utility of inertia to within-person means only, we find that inertia values explain 5.4% additional variance compared to a model with person-level means only. In the full ESM model, only person-level means of the content features of rumination (i.e., negativity and criticism) predict anxious symptoms.

Predictive value of ESM metrics compared to trait rumination

Trait rumination alone explains 33.9% of the variance of depression, $F(1, 37) = 20.47$, $p < .001$, and 22.5% of anxiety, $F(1, 37) = 12.06$, $p = .001$. The model combining ESM and trait rumination explains 62.6% of depression, $F(11, 27) = 6.771$, $p < .001$, and 41.3% of anxiety, $F(11, 27) = 3.431$, $p = .004$. Therefore, ESM metrics explain an additional 28.7% variance of depression and an additional 18.8% of anxiety. Conversely, trait rumination explains 8.7% additional variance of depression and 8.3% of anxiety compared to the ESM-only models.

For depression, only the effect of trait rumination ($p = .001$), negativity inertia ($p = .005$), and criticism SD were significant ($p = .043$). The effect of person-level means of the content features of rumination (i.e., negativity and criticism) was marginally significant ($p = 0.077$). Interestingly, the person-level means of the process features was no longer a significant predictor after including trait rumination. This could be due to trait rumination capturing what is measured by the mean of process features of rumination, considering their correlation ($r = .55$, $p < .001$). Looking at the standardized regression coefficients and their confidence intervals, we cannot say that trait rumination is a significantly stronger predictor than negativity inertia and criticism SD (see Figure 23). For anxiety, only the effect of trait rumination (p = .035) and person-level means of content features were significant (p = .017).

Figure 23. Plot of Standardized Regression Coefficients of Person-level Means, SD, and Inertia, and Trait Rumination Predicting Depressive Symptoms



Note. Process features means = composite variable of the person-level means of brooding, perseveration, and replaying; Content features means = composite variable of the person-level means of negativity and criticism; RMSSD process features = composite variable of the RMSSD of brooding, perseveration, and replaying; SD of process features = composite variable of the person-level SD of brooding, perseveration, and replaying.

10.3.3 Sensitivity analyses

Table 14. Cross-validation Results for Best Subset and Lasso Regressions Predicting Depression Symptoms

	Best Subset CV model			**Lasso CV model**		
Predictors	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***
			ESM variables only			
(Intercept)	-0.00	-2.52	**0.017**	-0.00	-2.48	**0.018**
PL means process features	0.59	4.89	**<0.001**	0.53	3.49	**0.001**
Inertia - negativity	0.30	2.58	**0.014**	0.28	2.23	**0.032**
Criticism SD	0.32	2.64	**0.012**	0.31	2.55	**0.015**
PL means content features				0.09	0.61	0.547
R^2 / R^2 adjusted	0.539 / 0.500			0.544 / 0.490		
	$F(3, 35) = 13.65$, $p < .001$			$F(4, 34) = 10.14$, $p < .001$		
			ESM variables and trait rumination			
(Intercept)	-0.00	-2.51	**0.017**	0.00	-3.53	**0.001**
PL means content features	0.38	3.71	**0.001**	0.21	1.57	0.127
Inertia - negativity	0.23	2.32	**0.027**	0.22	1.99	**0.055**
Criticism SD	0.55	4.68	**<0.001**	0.36	3.37	**0.002**
Negativity SD	-0.32	-2.57	**0.015**			
Trait rumination	0.58	6.04	**<0.001**	0.45	3.58	**0.001**
PL means process features				0.19	1.19	0.244
R^2 / R^2 adjusted	0.715 / 0.672			0.672 / 0.622		
	$F(5, 33) = 16.54$, $p < .001$			$F(5, 33) = 13.51$, $p < .001$		

Note. CV = cross-validated; PL means process features = composite variable of the person-level means of brooding, perseveration, and replaying; PL means content features = composite variable of the person-level means of negativity and criticism.

Depression

The results of the cross-validated analyses for depression are presented in Table 14. The two best cross-validated ESM models selected by the best subset and lasso regressions both contain the mean of process features of rumination, negativity inertia, and criticism SD. The lasso model also included the mean of content features of rumination as a predictor. The best-performing model based on adjusted R^2 is the best subset selection cross-validated model, which explains 50% variance of depression using ESM metrics only, $F(3, 35) = 13.65$, $p < .001$.

When also including trait rumination in the analyses, the best subset regression model contains the mean of content features of rumination, negativity inertia, criticism SD, negativity SD, and trait rumination as significant predictors. In contrast, the lasso regression also contains the mean of process features of rumination, but not the negativity SD. However, only the effect of trait rumination and criticism SD are significant. The model with the highest adjusted R^2 is the best subset model, which explains 67.2% of the variance of depression, $F(5, 33) = 16.54$, $p < .001$.

Anxiety

Table 15. Cross-validation Results for Best Subset and Lasso Regressions Predicting Anxiety Symptoms

	Best Subset CV			Lasso CV		
Predictors	***std. Beta***	***t***	***p***	***std. Beta***	***t***	***p***
	ESM variables only					
(Intercept)	0.00	1.19	0.240	0.00	-0.98	0.334
PL means content features	0.58	4.36	**<0.001**	0.43	2.67	**0.011**
Inertia - brooding				0.31	2.48	**0.018**
PL means process features				0.22	1.36	0.182
Inertia - negativity				0.22	1.67	0.104
R^2 / R^2 adjusted	0.339 / 0.321 $F(1, 37) = 18.97, p < .001$			0.480 / 0.419 $F(4, 34) = 7.858, p < .001$		
	ESM variables and trait rumination					
Intercept	0.00	-1.55	0.129	0.00	-1.55	0.129
PL means content features	0.50	4.27	**<0.001**	0.50	4.27	**<0.001**
Inertia - negativity	0.17	1.46	0.155	0.17	1.46	0.155
Inertia - brooding	0.22	1.88	**0.068**	0.22	1.88	**0.068**
Trait rumination	0.35	2.93	**0.006**	0.35	2.93	**0.006**
R^2 / R^2 adjusted	0.563 / 0.511 $F(4, 34) = 10.94, p < .001$			0.563 / 0.511 $F(4, 34) = 10.94, p < .001$		

Note. CV = cross-validated; PL means process features = composite variable of the person-level means of brooding, perseveration, and replaying; PL means content features = composite variable of the person-level means of negativity and criticism.

The results of the cross-validated analyses for anxiety are presented in Table 15. The best subset selection analyses only selected for the mean of the content features of rumination, this predictor alone explaining 32.1% variance of anxiety, $F(1, 37) = 18.97$, $p < .001$. The lasso regression analyses select as predictors of anxiety the mean of content features of rumination, the mean of the process features of rumination, brooding inertia, and negativity inertia. However, only the effects of brooding inertia and the mean of the content features of rumination are significant. The lasso regression model explains 41.9% of anxiety, $F(4, 34) = 7.858$, $p < .001$.

When also including trait rumination in the analyses, both methods lead to the same model. This model includes the mean of the content features of rumination, negativity inertia, brooding inertia, and trait rumination as predictors. However, only the effects of the mean of content features and trait rumination were significant, with the effect of brooding inertia being marginally significant. The model explains 51.1% of anxiety, $F(4, 34) = 10.94$, $p < .001$.

Overall, the results of the sensitivity analyses support the results of the hierarchical regression analyses. The resulting models however perform better than the models of the hierarchical regressions as the cross-validated best subset and lasso regression models are sparser and therefore better powered.

10.4 Discussion

Our study had two primary objectives. First, we aimed to determine if ESM-derived statistics of rumination features and temporal dynamics indices could predict depression and anxiety. We not only used person-level means and standard deviations but also used inertia and moment-to-moment variability (i.e., RMSSD). Furthermore, our second objective aimed at answering two critical questions related to the predictive utility of these metrics derived from intensive time-series data: (a) whether inertia and moment-to-moment variability provide any additional predictive value for depression and anxiety beyond person-level means and standard deviations, and (b) how the predictive utility of metrics derive from ESM compares to that of a measure of trait rumination.

ESM-derived statistics alone better predicted depression than anxiety, explaining 50% of depression's variance, compared to 41.9% for anxiety, based on the sparser cross-validated models. The predictors for depression included the mean of rumination's process features, negativity inertia, and criticism SD. When trait rumination was added, only negativity inertia and criticism SD remained significant. Interestingly, the variability of negativity was a significant predictor of depression in the best subset model in addition to trait rumination, negativity inertia, and criticism SD; this model explained 67.2% of the variance of depression. In contrast, anxiety was predicted by rumination's content features and brooding inertia, with only content features persisting after considering trait rumination; this model explained 51.1% of the variance of anxiety. Hence, our results revealed that inertia, but not RMSSD values, had predictive utility for depression even when controlling for person-level means and SDs, and even after controlling for trait rumination. Moreover, models combining both trait and momentary measures accounted for the most variance.

The findings regarding inertia and RMSSD are interesting. In line with previous results (e.g., Bos et al., 2019; Dejonckheere et al., 2019; Koval et al., 2013), RMSSD strongly correlated with SD and provided no additional predictive value. Conversely, inertia did add predictive value. These results are at odds with Dejonckheere's et al. (2019) meta-analysis, which found no added value from inertia after adjusting for person-level means. The fact that we derived the inertia values from a multilevel vector autoregressive model (mlVAR; Epskamp, Waldorp, et al., 2018) might explain this difference: the inertia values represent the residual autocorrelation of variables after accounting for the effect of all the other variables at the preceding time point. Although discussed on a theoretical level (Koval et al., 2021), this approach had not been used before. In our study, this residual inertia may have more predictive value because it reflects what is left after participants tried to regulate their emotions by ruminating. Lastly, the sample type might also help to explain the discrepancy in results: our sample was a community sample, but Dejonckheere's et al. (2019) meta-analysis contained both healthy and clinical samples. Note however that the previously cited studies were discussing emotional inertia, not the inertia of negative thoughts.

The result regarding negativity inertia warrants a more detailed interpretation. Only negativity inertia—not the inertia of other rumination features—predicted depression. Our findings align with the common view of depression as involving more negative thoughts, emotions, and a more negative mood on average (i.e., reflected in the person-level content features mean), but also their prolonged presence (i.e., negativity inertia). This finding complements prior studies linking rumination inertia, measured as a unitary construct, and depression (e.g., Bean et al., 2020; 2021). Indeed, our findings indicate that it is not only the repetitive nature of rumination or the tendency to ruminate that predicts depression but also the lingering nature of *negative* thoughts. Such lingering negativity might stem from the ineffectiveness of rumination at addressing the root cause of these negative thoughts (Hoebeke et al., 2023a). Over time, these lingering thoughts could lead to several adverse outcomes such as inflammation (Moons & Shields, 2015; Szabo et al., 2022), impaired immunity (Brod et al., 2014; D'Acquisto, 2017; Reed & Raison, 2016), and worse physical health and chronic health conditions (Curhan et al., 2014; Leger et al., 2018; Seiler et al., 2020)—all adding to the heterogenous experience of depression (Maydych, 2019).

Intriguingly, higher self-criticism variability (*SD*) significantly predicted worse depressive symptomatology. This suggests that those with depression might not uniformly criticize themselves across different aspects of daily life: they might not have self-critical thoughts constantly, but when these thoughts emerge—perhaps due to specific triggers—the intensity sharply contrasts with their average or lowest point. Conversely, non-depressed individuals might exhibit less variability in their self-critical thoughts, which could reflect more stable self-esteem or healthier standards for themselves. Therefore, high self-criticism variability could denote "self-criticism reactivity" to certain situations or triggers.

Negativity's SD was also a significant predictor of depression. Notably, it was only significant in the best subset cross-validated model that included trait rumination. Unlike criticism SD, a lower negativity variability was associated with increased depressive symptoms. Viewing negative thoughts as emotional proxies aligns this finding with research suggesting depression entails a blunted emotional life and lower emotional reactivity (Bylsma, 2021; Peeters et al., 2003; Rottenberg, 2005). However, this result, and the fact that moment-to-moment variability (RMSSD) did not add any predictive value in this study and previous research (Bos et al., 2019), contradicts studies linking affective variability with poorer well-being (Houben et al., 2015). Perhaps, there is no emotional "instability" in depression as had been hypothesized. Yet, accounting for the context in which variability is measured in future studies could perhaps reconcile discrepancies in results (Bylsma, 2021).

Lastly, our results highlight the predictive utility of ESM-derived metrics compared to a trait measure. ESM-only models outperformed trait rumination-only models. Furthermore, even after adjusting for trait rumination, ESM-derived statistics retained their predictive potency. These are consistent with a previous study that compared ESM assessment to paper and pencil questionnaires (Moore et al., 2016): the increased predictive power of ESM measures would seem to offset the burden of ESM. Notably, models integrating both ESM and trait rumination emerged as the most predictive of depression and anxiety. While trait rumination was the strongest predictor of depression, it was not significantly greater than person-level means, negativity inertia, or self-criticism variability. Moreover, it seems that trait rumination overtook the variance explained by the process features of rumination as (a) they were correlated ($r = .55$, $p < .001$) and (b) trait rumination is a stronger predictor than the process features alone. These findings suggest that while the RRS-10 captures overlapping and perhaps additional processes—including potential recall biases that might uniquely contribute to depression —ESM measures likely tap into the dynamic essence of rumination and predict depression better. In summary, ESM and trait measures seem to offer both overlapping and distinct insights into depression and anxiety.

Future research can build upon our findings in several ways. First, a primary limitation of our study was the small sample size. To account for this limitation, we conducted sensitivity analyses via cross-validated variable selection, which resulted in sparser and ostensibly more robust models. Yet, future studies should aim for a larger and more diverse participant pool, encompassing various symptom severities, to bolster the generalizability of findings. Second, our study did not measure or examine the context in which participants answered ESM surveys. Therefore, future studies could consider it, as the predictive utility of inertia and variability might be context-dependent: rigid versus variable responses in a context presenting little variability (e.g., alone at home watching television) versus a context with varied stimuli (e.g., a social setting). Lastly, item-level analyses of trait rumination, paralleling our approach with ESM items, could pinpoint which trait rumination items offer distinct information from ESM data.

In conclusion, these results provide additional support for the utility of using ESM measures compared to an equivalent trait measure, suggesting that the added burden of ESM may be justified. Moreover, inertia contributed additional predictive value even after controlling for person-level means, standard deviations, and trait rumination, whereas moment-to-moment variability (i.e., RMSSD) did not. Therefore, we encourage future ESM research to systematically consider person-level means, SDs, and inertia of rumination features, as well as potential interactions in different contexts. Indeed, all three metrics might inform about different facets of the dynamic fingerprints of mental disorders.

Section 3.

Clarifying the associations between rumination & executive control

Chapter 11.

The impact of transcranial Direct Current stimulation on rumination: A systematic review of the sham-controlled studies in healthy and clinical sample

Introduction. Broadly considered a transdiagnostic feature of psychological disorders, rumination is associated with lower treatment response, slower recovery rates, and higher relapse rates. Accordingly, research has focused on the development of interventions to alleviate rumination. Recently, transcranial Direct Current Stimulation (tDCS) has emerged as a promising tool to do so.

Methods. We performed a systematic review of sham-controlled tDCS studies targeting rumination among healthy participants or patients with psychiatric disorders, investigating the effectiveness of tDCS in reducing rumination, and assessing the research quality of this nascent field.

Results. We identified nine studies, with five reporting a significant impact of tDCS on rumination. We also outlined a few tDCS parameters (e.g., stimulation duration, electrode size) and research methods' features (e.g., within- versus between-research designs) characterizing those positive-finding studies. However, these studies were characterized by substantial heterogeneity (e.g., methodological flaws, lack of open science practices), precluding any definite statement about the best way to target rumination via tDCS. Moreover, several strong methodological limitations were also present across those studies.

Discussion. Although our systematic review identifies the strengths and weaknesses of the available research about the impact of tDCS on rumination, it calls for strong efforts to improve this nascent field's current methodological caveats. We discuss how open science practices can help to usher this field forward.

Reference
Hoebeke, Y., Desmedt, O., Özçimen, B., & Heeren, A. (2021). The impact of transcranial Direct Current stimulation on rumination: A systematic review of the sham-controlled studies in healthy and clinical samples. *Comprehensive Psychiatry*, *106*, 152226. https://doi.org/10/f83m

11.1 Introduction

Transcranial direct current stimulation (tDCS) is a non-invasive brain neuromodulation technique that has become a hot topic in contemporary clinical neuroscience as it can, through the modulation of brain cortical excitability, modulate cognitive and motor domains (Fregni & Pascual-Leone, 2007; Nitsche & Paulus, 2001a). It consists of the application of a weak, direct electric current through two electrodes, an anode and a cathode. These two electrodes are positioned over one's scalp to reach the neuronal tissue and induce polarization-shifts (i.e., the current flows from the anode to the cathode) on the resting membrane potential without triggering action potentials per se (Brunoni et al., 2012; Nitsche et al., 2008). In this way, although individual responses to stimulation are not uniformly excitatory or inhibitory (Jacobson et al., 2012), anodal tDCS is generally considered excitatory while cathodal tDCS is generally considered inhibitory (Radman et al., 2009).

One of the strengths of tDCS is that it allows research blinding (Nitsche et al., 2008). Indeed, many studies included the sham stimulation wherein the electrodes' position is identical to the active tDCS condition but with the current ramping down after a few seconds (e.g., 30 seconds). This procedure has become commonly used in tDCS research and is known to be a way to provide the initial sensation of stimulation without the subsequent effects on cortical excitability (Nitsche et al., 2008; Ohn et al., 2008, but see Fonteneau et al., 2019; Horvath et al., 2014; O'Connell et al., 2012; Turi et al., 2019). Lastly, many studies have also relied on tDCS devices allowing full double-blind study design, highlighting the promise of this procedure in terms of research quality (Nitsche et al., 2008).

Because of its non-invasive nature, highly controlled sham condition, and relatively low cost compared to other neuromodulation techniques such as the transcranial magnetic stimulation (TMS), tDCS quickly arose as a promising therapeutic tool. Indeed, several systematic reviews and meta-analyses of randomized controlled trials indicated the safety and therapeutic efficacy of tDCS for a wide range of mental disorders (Tortella et al., 2015), including, among others, depression and mood disorders (Borrione et al., 2018; Dondé et al., 2018; Razza et al., 2020), anxiety disorders (Stein et al., 2020; Yosephi et al., 2019), psychotic disorders (E. H. M. Lee et al., 2018), pain-related disorders (Zortea et al., 2019), substance use disorders (Lupi et al., 2017), and eating disorders (Dalton et al., 2018). Hence, this literature has prompted an exceptionally positive prospect vis-à-vis tDCS as a therapeutic tool.

However, although the impact of tDCS has not been confined to symptoms of mental disorders (Heeren et al., 2017; Silva et al., 2017), uncertainty still abounds regarding the psychological mechanisms that may mediate the effects of tDCS on such a broad range of mental disorders. The only psychological mechanism that has been extensively studied so far in the understanding of the impact of tDCS across mental disorders is working memory (Brunoni & Vanderhasselt, 2014; Hill et al., 2016). Comprehensive research on other mechanisms that may mediate the impact of tDCS on symptom reduction remains rather scarce.

Rumination is perhaps the prime example of such a mechanism (Mansell et al., 2008; Watkins, 2015a). Rumination is classically defined as a perseverative, passive, self-focused thinking about the content, causes, and consequences of one's self, feelings, personal concerns, and upsetting experiences, without taking any problem-solving action (Nolen-Hoeksema et al., 2008). It is involved in the onset and maintenance of depression and anxiety disorders (McLaughlin et al., 2014; McLaughlin & Nolen-Hoeksema, 2011b). Moreover, high rumination rates predict slower treatment response, lower rates of recovery, and higher rates of relapse in mood and anxiety disorders (Ciesla & Roberts, 2002; Schmaling et al., 2002). Finally, recent research has pointed to rumination as a viable and plausible target for transdiagnostic clinical interventions (Spinhoven et al., 2018; Watkins, 2015a). Altogether, rumination thus appears as a plausible transdiagnostic feature of psychological disorders (Harvey et al., 2004; McLaughlin & Nolen-Hoeksema, 2011b; Nolen-Hoeksema & Watkins, 2011).

At the brain level, one common hypothesis shared across several prominent cognitive models of psychopathology is that rumination reflects impairments in top-down executive control, and that this failure results from a decreased activation of the prefrontal cortex, particularly of its dorsolateral part (dlPFC) (De Lissnyder et al., 2012; De Raedt, Hertel, et al., 2015; Koster et al., 2011; Whitmer & Banich, 2007). Clinical and laboratory research have accordingly aligned with this perspective. First, research has extensively demonstrated the existence of strong associations between rumination and reduced top-down executive control, particularly in terms of difficulty to inhibit prepotent responses and shifting from one task to another (for recent meta-analyses, see (Yang et al., 2017; Zetsche et al., 2018)). Moreover, there is mounting evidence indicating that improvement in executive control may mitigate rumination (Bomyea & Amir, 2011; Hoorelbeke et al., 2015; Siegle et al., 2014). Second, beyond behavioral research, neuroimaging research has also lent strong credence to the hypothesis that dlPFC is critically involved in the onset of rumination, at both the structural (i.e., cortical thickness) (Späti et al., 2015) and functional levels (Cooney et al., 2010; Forster et al., 2015).

Recently, clinical promises have arisen from neuromodulation research. Several studies have indeed indicated that one can, as compared to sham stimulation, reduce rumination via a transient increase of the neural activity within the left dlPFC via anodal tDCS in both healthy and clinical samples (Baeken et al., 2017; De Raedt et al., 2017). Given the transdiagnostic nature and clinical relevance of rumination, these tDCS studies have prompted an especially enthusiastic appraisal vis-à-vis the prospects of tDCS as a new intervention ripe for targeting rumination (Baeken et al., 2017; De Raedt et al., 2017).

However, other studies failed to report such an effect (e.g., Clarke et al., 2020). As such, uncertainty remains regarding the ability of tDCS to yield a reliable and robust impact on rumination. Moreover, prior research revealed that both tDCS-related parameters (e.g., montage, stimulation intensity) and inter/intraindividual factors (e.g., age, physiological state) may modulate tDCS effects (Chew et al., 2015; Li et al., 2015). In this way, one cannot exclude that study-to-study variations in stimulation parameters, montage, sample characteristics, and research protocols modulate tDCS' impact on rumination and may explain these mixed findings.

Therefore, the main goal of this project was to conduct a systematic review of the sham-controlled studies conducted among healthy and clinical samples, investigating the impact of tDCS on rumination. Following previous tDCS-related systematic reviews (Brunoni & Vanderhasselt, 2014), we included studies relying on a between-subject or within-subject design. As recent systematic reviews on tDCS highlighted the study-to-study variations in terms of stimulation parameters (M. E. Berryhill & Martin, 2018; Dedoncker et al., 2016a; Meron et al., 2015), we also aimed at examining the potential impact of these parameters in light of the results of this systematic review. Finally, we also aimed at evaluating the methodological quality of this nascent field of research.

11.2Methods

We conducted a systematic review according to the PRISMA recommendations (Moher et al., 2009, 2015); for the PRISMA checklist, see the file available on the Open Science Framework (https://osf.io/suaf4/). The data extraction and synthesis plan of this systematic review were preregistered on PROSPERO (https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=118540— Identifier: CRD42018118540).

11.2.1 Literature search

YH conducted a systematic literature search through November 2019 via PubMed, PsycInfo, and Scopus, using the following search terms: "tDCS" or "transcranial direct current stimulation" or "brain stimulation" or "neuro modulation" or "direct stimulation" or "transcranial electric stimulation" or "electric stimulation" or "non-invasive brain stimulation" combined with "rumination" or "repetitive negative thinking" or "post event processing" or "post-event processing" or "negative thinking" or "repetitive thinking" or "worry" or "repetitive thought" or "brooding" or "intrusive thoughts" or "ruminative" or "worrying" or "self-reflection". YH and AH reviewed and piloted this search string before conducting the literature search. It comprises various terms that may be used in the literature to refer to tDCS and terms conceptually analog to rumination. We updated the reference list on the 17th of February 2020 using the same search string on PubMed. For each database, the exact formatted codes for the search string have been available on the Open Science Framework's account of this project (https://osf.io/gu3na/).

11.2.2 Selection criteria

We included studies that met the following PICOS criteria (Liberati et al., 2009) as follows: (a) Participants: adult participants, male or female, either healthy volunteers or clinical patients; (b) Intervention: tDCS; (c) Comparison: sham stimulation; (d) Outcomes: at least one state or trait measure of rumination (and analog terms such as worrying) as a dependent variable; (e) Study design: single or double-blind controlled study; (f) Publication type: published in a peer-reviewed journal, written in English. We excluded single case studies as well as studies devoid of sham-stimulation control condition. YH and BO screened the abstracts and titles independently. The inter-rater agreement between them was high (Kappa value: 0.81), and the discrepancies were resolved through discussion. YH then screened the full texts.

11.2.3 Data extraction

Two authors (YH and OD) extracted the data according to a predefined list of relevant information, which was built upon previous systematic reviews and tDCS research (Dedoncker et al., 2016a; e.g., Hill et al., 2016; K. T. Jones et al., 2015; Schade et al., 2012). With a kappa value of 0.86, the inter-rater agreement between them was high. The discrepancies were resolved through a discussion with a third author (AH). The main extracted variables were as follows: (a) sample size, (b) type of population (healthy vs clinical samples), (c) handedness (i.e., whether the researchers only recruited right-handed participants), (d) mean age, (e) percentage of women in the sample, (f) blinding, (g) study design (within-subjects or between-subjects), (h) compensation (whether participants received a financial compensation or course credits in exchange for their participation), (i) groups, (j) anode placement, (k) cathode placement, (l) whether the electrodes placement was cephalic (i.e., the two electrodes are placed over the scalp) or not), (m) stimulation intensity, (n) electrode size, (o) stimulation duration, (p) ramping parameters (e.g., 30-sec ramp-up and 30-sec ramp-down), (q) sham parameters (i.e., whether the current was briefly ramped-up and -down prior and after to absence of stimulation , and, if so its duration and intensity), (r) the interval between sessions (if within-subject design or multi-sessions), (s) the presence of a stressor , (t) the name of the state measure of rumination (if included), (v) the name of the trait measure of rumination (if included). Table 16 depicts the extracted data.

11.2.4 Quality assessment

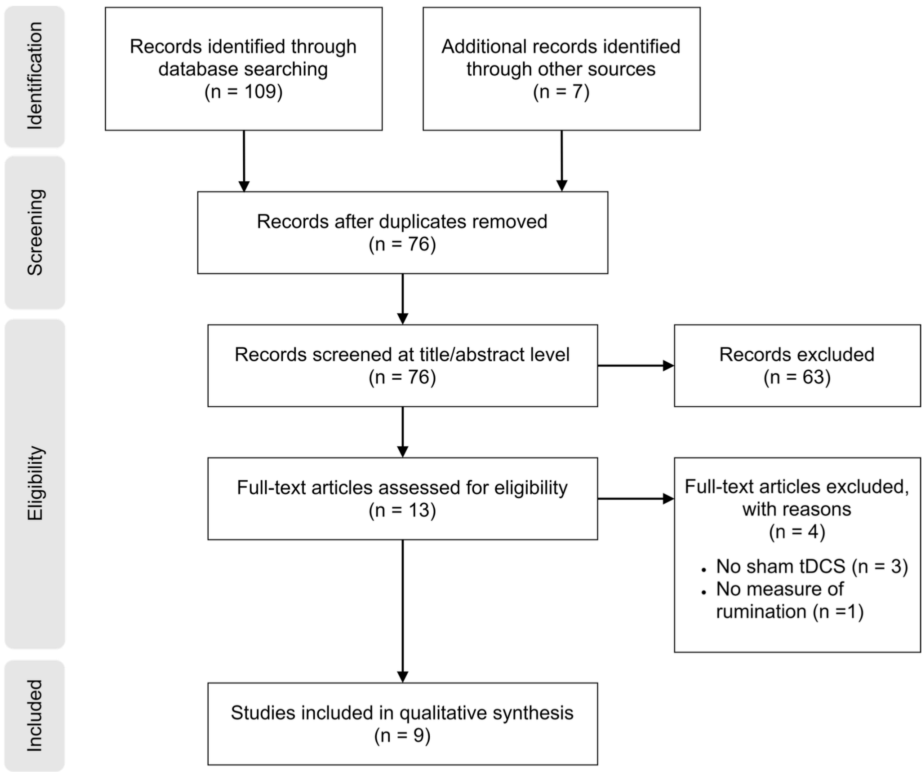
We assessed the studies' quality using the "RoB2" tool of the Cochrane Collaboration (Sterne et al., 2019). This tool aims at determining the possible sources of bias in randomized trials: (a) randomization process, (b) deviations from intended interventions, (c) missing outcome data, (d) measurement of the outcome, (e) selection of the reported results. This tool comprises a series of signaling questions within each domain that aim to elicit information about the study’s features relevant to the risk of bias. A decision algorithm then generates a judgment about the risk of bias from each domain, based on the signaling questions, and also creates an overall risk of bias. Two authors (YH and OD) independently evaluated the risk of bias for each study. The inter-rater agreement was high, with a *kappa* value of 0.61. The few discrepancies were resolved through a discussion with a third author (AH).

11.3Results

11.3.1 Study Selection

Figure 24 depicts the PRISMA flowchart diagram, summarizing the flow of information from identification to studies' inclusion (Moher et al., 2009, 2015). Our search strategy identified 109 publications, of which 40 were duplicates. To consider the latest publications, a final search on PubMed identified seven additional records on the 17th of February 2020. We removed duplicates and then screened the abstracts from the remaining 76 publications. We excluded 63 papers from this step, as they were review articles, qualitative studies, case studies, dissertation abstracts, study protocols, and non-English articles. We further screened the remaining 13 articles, and we excluded four articles for the following reasons: (a) Rumination was not a dependent variable (*n* = 1); (b) The study did not include a sham tDCS group (*n* = 3). After applying these exclusions, we found that nine studies satisfied the inclusion criteria (see Figure 24).

Figure 24. PRISMA Flow Diagram



11.3.2 Quality assessment

As shown in Figure 25, the overall risk of bias was high, with four studies exhibiting a high risk of bias, and the five remaining ones showing some concerns. When looking at the criterion individually (see Figure 25), two characteristics stood out: only one study exhibited a low risk of bias regarding the random sequence generation, and none of the studies was free of potent, selective reporting. On the other hand, most studies exhibited a low risk of bias in terms of deviations from the intended intervention, processing of missing outcome data, or outcomes measurement. Altogether, these results suggest that random sequence generation and selective reporting were the two most problematic quality criteria. Note that only one study was pre-registered, but discrepancies were identified between the pre-registered protocol and the published research.

Figure 25. Risk of Bias Assessment

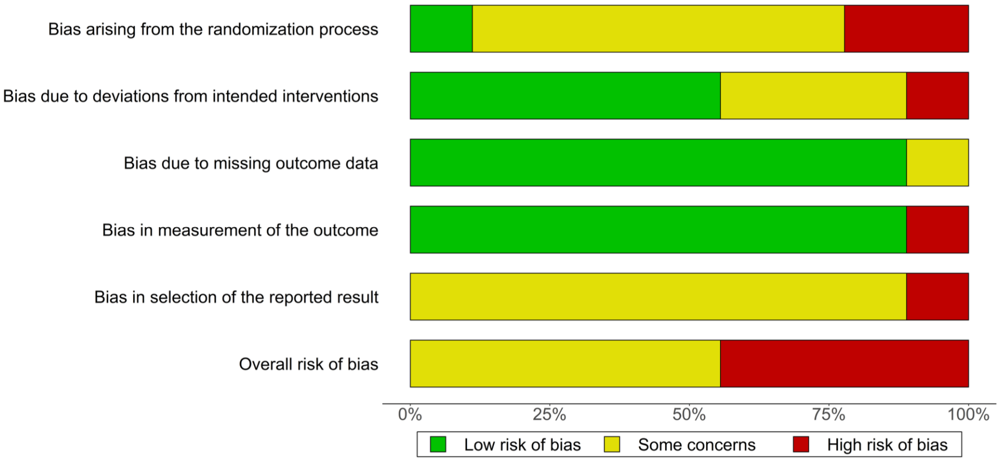


Table 16. Sample characteristics, design of the studies, online task characteristics, and rumination measures characteristics

Study	Sample characteristics					Protocol characteristics				Online task	Stressor	Rumination measure		Location
	N	**Type**	**Handed-ness**	**Mean Age**	**% Women**	**Blinding**	**Design**	**Compe-nsation**	**Conditions (*n*)**			**State**	**Trait**	
Baeken et al. (2017)	40	H	R	22.55	100	S	W-S	F	(a) tDCS; (b) sham tDCS	None	No. 5 min resting period.	MRSI		BE
Clarke et al. (2020)	95	H		22.13	78.9	S	B-S		(a) tDCS + mindfulness (*25*); (b) tDCS + mind wandering (*25*); (c) sham tDCS + mindfulness (*23*); (d) sham tDCS + mind wandering (*22*)	Mindfulness body scan	Participants were asked to actively worry for 5 min	Frequency of negative intrusive thoughts during a mindful breathing task		AU
De Raedt et al. (2017)	32	H	R	22.6	100	S	W-S	F	(a) tDCS; (b) sham tDCS	None	Listening to audio of criticizing comments	MRSI		BE
De Putter et al. (2015)	66	H		23.09	80.3	D	B-S	F	(a) tDCS + WM training (*22*[b]); (b) tDCS control training (*22*); (c) sham tDCS (*22*)	WM training and Control training	No. 10 min resting period.	MRSI	RRS	BE

Study	Sample characteristics					Protocol characteristics				Online task	Stressor	Rumination measure		Location
	N	Type	Handed-ness	Mean Age	% Women	Blinding	Design	Compe-nsation	Conditions (*n*)			State	Trait	
Kelley et al. (2013)	90	H	R		66.6	D	B-S	C	(a) bipolar tDCS, anode on left dlPFC (*29*); (b) bipolar tDCS, anode on right dlPFC (*28*); (c) sham tDCS (*33*)	None	Negative feedback on essay (after 10 min of tDCS) [a]	10 item state rumination measure + thought listing procedure		USA
Movahed et al. (2018)	18	*GAD*		28.7	46	S	B-S		(a) tDCS (*6*); (b) sham tDCS (*6*); (c) pharmacotherapy (*6*)	None			PSWQ	IR
Vanderhasselt et al. (2013)	32	H	R	22.28	62.5	S	W-S		(a) tDCS; (b) sham tDCS	IST	No. 8 min resting period.	MRSI	RRS	BR
Vanderhasselt et al. (2015)	33	*MDD*	R	44.03	72.7	D	B-S		(a) tDCS (*19*); (b) sham tDCS (*14*)	PASAT training			RRS	BR
Voss et al. (2018)	118	H	R	23.32	100	D	B-S	F & C	(a) tDCS, anode on left dlPFC (*40*); (b) tDCS, cathode on left dlPFC (*38*); (c) sham tDCS (*40*)	modified CVLT	Film with violent content followed by 10 min resting period	Modified PTQ	Modified PTQ	DE

Note. The dash means that data were not reported. GAD = General Anxiety Disorder; H = Healthy; R = right-handed; S = Single blinding; D = double blinding; W-S = within-subjects; B-S = between-subjects; F = financial; C = course credits; WM = working memory; MRSI = Momentary Ruminative Self-Focus Inventory; PTQ = Perseverative Thinking Questionnaire; RRS = Ruminative Response Scale; PSWQ = Penn State Worry Questionnaire; PASAT = Paced Auditory Serial Addition Task; CVLT = California Verbal Learning Test. [a] Participants read this negative feedback during the last 5 min of tDCS stimulation. [b] Not reported, but participants were randomly assigned to the 3 groups, thus if it is equal groups, it is 22 participants per group.

Table 17. TDCS parameters and summary of results

Study	tDCS Parameters								Sham parameters	Electrode placement determination	N of active tDCS sessions	BSI	Summary of results
	Montage Type	Anode location	Cathode location	Current Density (mA/cm²)	Intensity (mA)	Electrode Size (cm²) and Shape	Duration (min)	Ramp-up; ramp-down (s)					
Baeken et al. (2017)	Cephalic	Left dlFPC	Contralateral supraorbital area	0.06	1.5	25 rectangular	20	30; 30	Ramping the current up and down	Neuronavigation	1	>48h	Anodal tDCS on the left dlPFC reduced state rumination compared to sham
Clarke et al. (2020)	Extra-cephalic	Left dlFPC	Left superior trapezius muscle	0.0667	2	30	20	30; 30	1 min of 1mA stimulation between ramp-up and ramp-down	10-20 system	1		*No effect of anodal tDCS on intrusive thoughts*
De Raedt et al. (2017)	Cephalic	Left dlFPC	Contralateral supraorbital area	0.0429	1.5	35	20	30; 30	Ramping the current up and down	Neuronavigation	1	>48h	Anodal tDCS on the left dlPFC reduced rumination compared to sham
De Putter et al. (2015)	Cephalic	Left dlFPC	Contralateral supraorbital area	0.08	2	25	25	30; 30	Ramping the current up and down	10-20 system	1		*No effect of anodal tDCS on rumination*

Study	tDCS Parameters								Sham parameters	Electrode placement determination	N of active tDCS sessions	BSI	Summary of results
	Montage Type	Anode location	Cathode location	Current Density (mA/cm²)	Intensity (mA)	Electrode Size (cm²) and Shape	Duration (min)	Ramp-up; ramp-down (s)					
Kelley et al. (2013)	Bihemis-pheric	(a) Left dlPFC (b) Right dlPFC	(a) Right dlPFC (b) Left dlPFC	0.0571	2	35 rectangular	15	5; 5	30 s of 1mA stimulation between ramp-up and ramp-down	10-20 system	1		Bihemispheric tDCS stimulation, with the anode on the right dlPFC and the cathode on the left dlPFC increased state rumination, compared to the opposite montage and to sham.
Movahed et al. (2018)	Extra-cephalic	Contra-lateral deltoid muscle	Right dlPFC		2		20				10 sessions over 4 weeks		Cathodal tDCS on the right dlPFC decreased worry at post-test and 2 months follow-up.
Vanderhasselt et al. (2013)	Cephalic	Left dlFPC	Contralateral supraorbital area	0.0571	2	35	20	30; 30	Ramping the current up and down	10-20 system	1	>48h	The influence of anodal tDCS on left dlPFC on rumination was mediated by the enhancement of WM operations

Study	tDCS Parameters								Sham parameters	Electrode placement determination	N of active tDCS sessions	BSI	Summary of results
	Montage Type	**Anode location**	**Cathode location**	**Current Density (mA/cm²)**	**Intensity (mA)**	**Electrode Size (cm²) and Shape**	**Duration (min)**	**Ramp-up; ramp-down (s)**					
													for angry faces (but no direct effect of tDCS on rumination was found)
Vanderhasselt et al. (2015)	Bihemis-pheric	Left dlFPC	Right dlPFC	0.08	2	25 rectangular	30	30; 15	Ramping the current up and down	10-20 system	10 sessions over 2 weeks/10 working days		*WM training reduced brooding among depressive patients but neuromodulation of the dlPFC did not have any supplementary effect on the reduction of rumination*
Voss et al. (2018)	Extra-cephalic	(a) Left dlPFC (b) Contra-lateral deltoid muscle	(a) Contra-lateral deltoid muscle (b) Left dlPFC	0.0286	1	35	20	5; 5	30 s of 1mA stimulation between ramp-up and ramp-down	10-20 system	2		*No effect of tDCS on rumination was found nor was there any interaction with the WM task*

Note. The dash means that data were not reported. BSI = between session interval: dlPFC = dorsolateral prefrontal cortex; WM = working memory.

11.3.3 Summary of the main studies' findings

As depicted in Table 17, five out of the nine studies reported that tDCS significantly alleviated rumination. In two studies, anodal tDCS on the left dlPFC significantly reduced state rumination, as compared to sham stimulation (Baeken et al., 2017; De Raedt et al., 2017). In one study (Vanderhasselt et al., 2013), this effect was found only through the mediation of the enhancement of WM operations. In another study (Kelley et al., 2013), a bihemispheric tDCS-montage (anode on the right dlPFC and the cathode on the left dlPFC) increased state rumination, as compared to the opposite tDCS-montage (i.e., the anode on the left dlFPC and the cathode on the right dlPFC) and sham stimulation. Finally, one study (Movahed et al., 2018) indicated that a 10-session cathodal stimulation program (over the right dlPFC) reduced trait worry compared to sham stimulation, among patients with a general anxiety disorder. The four other studies did not report any direct effect of tDCS on state or trait ruminations.

11.3.4 Characteristics of included studies

Sample Characteristics

Table 16 and Table 17, summarize the main characteristics of the nine studies. The sample size varied from 18 to 118 participants. Three studies recruited only women, and most of the studies had more women than men (average = 81.39 % of women; min = 46%; max = 100%). Note that only De Raedt et al. (De Raedt et al., 2017) provided a justification for this restriction to women; the other studies did not. Participants' mean age across studies was 26.08 years old (*SD* = 7.56). And whereas six studies recruited right-handed participants, the others did not report participants' handedness.

Only two studies had a clinical sample qualifying either for generalized anxiety disorder (Movahed et al., 2018) or major depressive disorder (Vanderhasselt et al., 2015); others relied exclusively on healthy volunteers.

Study Design

Three studies relied on a within-subjects design; each study including a between-session interval of at least 48 hours. Moreover, the two studies relying on a clinical sample included multiple sessions of active tDCS (Movahed et al., 2018; Vanderhasselt et al., 2015). Details are available in Table 17. In terms of the blinding, only four studies had a double blinding procedure. Finally, five studies included a participant's compensation—either financial compensation or course credits.

Assessment of Rumination

As shown in Table 16, two in nine studies did not assess state rumination (i.e., to which extent one is ruminating now), and focused only on trait rumination (i.e., one's general tendency to ruminate). Note that these two studies were conducted in clinical samples. Five studies assessed trait rumination, with most of them (n = 3) relying on the Ruminative Response Scale (RRS; Treynor et al., 2003).

Among the seven studies assessing state rumination, there were variations in the way state rumination was captured. On the one hand, as individuals naturally tend to ruminate when confronted with stressors, four studies included a laboratory stressor to elicit rumination (for details about the stressors, see Table 16). As shown in Table 16, except for Kelley and al. (Kelley et al., 2013), the stressor and the measurement of post-stressor state rumination were administered offline (post-tDCS stimulation) among these studies. On the other hand, three studies did not include any formal laboratory stressors to induce rumination but relied on a rest period to do so. This rest period was placed between the end of the stimulation and the assessment of state rumination. As depicted in Table 16, rest periods lasted either, 5, 8, or 10 min. Moreover, most studies (*n* = 4) assessed state rumination via the Momentary Ruminative Self-Focus Inventory (MRSI; Marchetti et al., 2018b).

Tasks administered during tDCS (online task)

As depicted in Table 16, five studies had a task administered simultaneously to the stimulation (i.e., online tasks). In four studies, it was computerized cognitive tasks tapping onto working memory. In one study, it was a mindfulness body scan procedure (Clarke et al., 2020).

tDCS Parameters and Electrodes' Placements

The distinct stimulation parameters are summarized in Table 17. The most commonly used parameters were as follows: a stimulation intensity of 2 mA (*n* = 6), a stimulation duration of 20 min (*n* = 5), an electrodes' size of 35 cm^2 (*n* = 4), and a ramping-up and ramping-down of the direct current intensity of 30 sec each (*n* = 5). Interestingly, only three studies explicitly reported the shape of the electrodes (see Table 17). However, there were large study-to-study variations in terms of electrodes' placements (see Table 17). Although eight in nine studies had the anode located over the left dlPFC, cathode placement was not consistent across studies. Six studies had a cephalic montage with either the cathode placed over the contralateral supraorbital area (*n* = 4) or a bihemispheric ("lateralized") montage over the dlPFC (*n* = 2). Studies using bihemispheric montages are based on the assumption that by stimulating simultaneous homotopic regions (with an anode and a cathode), the interhemispheric balance will shift towards the anode, thus potentially favoring the cognitive processing performed on that hemisphere (Jacobson et al., 2012). Moreover, one study had a montage wherein the cathode was placed over the right dlPFC and the anode over the contralateral deltoid muscle (Movahed et al., 2018). Note that 8 studies of the 9 provided information about the exact procedure used for the electrode placement. Among those, the electrodes' placement was determined either via neuronavigation tools (*n* = 2 studies) or in accordance with the international 10-20 system of electrode placement along with manual measurement to align with this system (*n* = 6).

Finally, regarding the sham stimulation, three different types of scenarios were identified. In the first scenario, the current was ramped-up, then ramped-down immediately (*n* = 5). In the second one, the current was ramped-up, then maintained during 30 s, and finally ramped-down (*n* = 2). Finally, the current was ramped-up, then turned on for 1 min at 1 mA, and ramped-down (*n* = 1).

11.4 Discussion

In this systematic review, we aimed at providing a comprehensive examination of the sham-controlled tDCS studies targeting rumination among healthy participants or patients with psychiatric disorders, and to assess the research quality of this nascent field. Through this process, nine studies were identified, with only five reporting a significant impact of tDCS on rumination. However, although we did our best to try identifying the most desirable combination of tDCS parameters and methodological features across these five studies reporting a significant impact of tDCS on rumination, these studies were characterized by substantial heterogeneity; thus, precluding any definite statement about the impact of tDCS on rumination. Hereafter, we discuss the critical issues and questions raised by this systematic review.

This review's central finding is the high heterogeneity between studies (e.g., study protocol, tDCS parameters, rumination measures). Although heterogeneity can somewhat be viewed as a strength, in the present case, it precludes any reliable inferences regarding which combination of parameters works or does not. Therefore, it is essential to converge towards the use of more uniformized protocols, and then examine consistency of the findings across iterations. However, despite the heterogeneity, one can strikingly summarize the most frequent tDCS parameters across studies as follows: a stimulation duration of 20 minutes, a stimulation intensity of 2 mA, and 35 cm^2 electrodes. The most frequently reported sham parameters were a 30-sec ramping-up of the stimulation intensity, immediately followed by ramping down the stimulation intensity for 30 sec. Of course, the fact that these parameters stand out as the most common in the present systematic review does not imply that they are the best ones to tap precisely onto rumination. In contrast, it is worth noting that these parameters (current density higher than 0.0029 mA/cm^2 and stimulation duration longer than 10 minutes) have been identified as the most optimal ones in previous systematic reviews and meta-analyses looking at the impact of tDCS on other cognitive processes (Dedoncker et al., 2016a; Hill et al., 2016). Moreover, note that the use of 35cm^2-size electrodes, a current intensity of 2mA, and a 20-min duration stimulation have been explicitly recommended as the "gold standard" parameters in the application of tDCS to enhance attention, learning, and memory, in both healthy and clinical populations (Coffman et al., 2014).

Beyond the tDCS parameters, a few study's characteristics also stood out among the studies that did achieve to impact on rumination via tDCS: except Movahed et al. (2018), they mostly relied on a within-subject design, included right-handed participants only, and compensated participants for their participation. And, although they may appear anecdotal, these three features should not come as a surprise as they have been already pointed out in other works: (a) a within-subject design is the most common design in tDCS studies (Woods et al., 2016); (b) handedness is critical to control for as tDCS stimulation yields different results in a right-handed population compared to left-handed or mixed-handed people (Schade et al., 2012); and (c) ensuring that participants' incentives are high improves the effectiveness of tDCS (Di Rosa et al., 2019; K. T. Jones et al., 2015). Lastly, although researchers assessed rumination with various measures, each single session tDCS study comprised a resting period prior to the administration of the state rumination measure. Future iterations of studies investigating the effect of tDCS on rumination could thus rely on the combination of these parameters – or give a rationale to explain different design choices – and see whether these results replicate across different laboratories, countries, and samples. One may also wonder whether we could identify specific sets of parameters (e.g., other electrode placement, other stimulation duration) that may drive the null-findings studies. Yet, the heterogeneity between these studies was considerable, and we were unable to identify any specific pattern of parameters or research design's features that would automatically thwart the impact of tDCS on rumination.

This systematic review has conceptual, methodological, and practical implications. In the brain imaging literature, rumination has been associated with activation within the dlPFC (Cooney et al., 2010) and broader cerebral networks (Disner et al., 2011). Accordingly, recent models (De Raedt & Koster, 2010; Koster et al., 2011) have given the dlPFC a central role. Thus, the studies' results in this systematic review dovetail with the hypothesis that the dlPFC may play a pivotal role. On the other hand, although rumination involves the dlPFC, it also relies on other regions, such as the inferior parietal lobe (Chou et al., 2020; Watkins & Roberts, 2020). Future iterations may also want to examine the potential impact of targeting those regions. At a methodological level, some of the heterogeneity problems mentioned earlier are not specific to the rumination research field but concern the entire tDCS research literature: the tDCS montage, the sample (i.e., sample characteristics or sample size), and open science practices. Different aspects could be improved. For instance, many studies were imprecise about their randomization process, their *a priori* sample calculation (for a discussion about tDCS studies and the importance of sample size, see (Minarik et al., 2016)), and future studies would need to be more transparent. Additionally, although we did not extract whether researchers checked and reported adverse effects, future studies should do so as adverse effects might render the blinding procedure ineffective (O'Connell et al., 2012).

There was a general lack of open science practices in the reviewed studies. Pre-registrations, sharing anonymized data in publicly accessible repositories (e.g., OSF), sharing code, and computerized tasks would usher the field forward (for a discussion, see Crüwell et al., 2019). If researchers moved in this direction, it would maximize transparency, research quality, and replicability. In other scientific domains, such open science research practices have already yielded striking impacts. For example, after 2000 (after registration was required in this field), only 8 % of the studies investigating the treatment or prevention of cardiovascular disease showed a significant benefit of the intervention, whereas 57 % of studies published before 2000 did (Kaplan & Irvin, 2015). Therefore, we believe that open science practices are a critical next step for the field.

The present findings might yield some clinical implications. If the observation that tDCS impacts rumination should turn to be true, it would allow brand new translational interventions for rumination. But to do so, researchers should move to clinical samples and conduct sufficiently powered randomized controlled trials comparing tDCS to treatment as usual, and not only rely on laboratory studies in small-sized healthy samples. Movahed et al. (2018) have already set the scene for such a translation, though their sample size was minimal (n by group = 6). Future iterations would thus want to determine which stimulation parameters, montage, sample characteristics, and research protocols ultimately magnify the effect of tDCS on rumination compared to treatment as usual. On the other hand, it is not always a guarantee that the group-level findings can generalize to the individual's level required for the case-conceptualization and clinical recommendations of a specific client (A. J. Fisher et al., 2018). Thus, intensive idiographic approaches may help clarify, and best understand the clinical value of tDCS integration in the treatment routine (for examples of such idiographic approaches, see F. Bos et al., 2018; Dotterer et al., 2019; Wright & Zimmermann, 2019). Lastly, only two studies investigated the effect of repeated sessions of tDCS. Therefore, researchers should further conduct studies with repeated sessions of tDCS and follow-up assessments as evidence suggests that longer trials with a higher number of sessions are associated with better outcomes (e.g., Ljubisavljevic et al., 2016; Valle et al., 2009).

Our systematic review also highlights some limitations that require further investigation in future research. First, the impact of completing a task during the stimulation is unclear in the tDCS literature. The same question applies to the stressor: all but one study (Kelley et al., 2013) used an offline stressor. A critical step in future iterations would thus be to clarify the respective impacts of online *versus* offline stressors as well as of online *versus* an offline task's completion. Moreover, although it is commonly assumed that anodal stimulation increases cortical excitability and that cathodal stimulation decreases cortical excitability, research has shown that this is not always the case; anodal and cathodal stimulation can have asymmetric effects to the ones expected, especially in the context of tDCS studies focusing on cognitive processes (Jacobson et al., 2012; Varoli et al., 2018). Therefore, investigating how the type of task and stressor (and when they are used) influences the effect of tDCS is especially relevant as tDCS does not induce activity in resting neural networks but modulates cortical excitability, plasticity, and functional connectivity by interacting with concurrent brain activity (Fritsch et al., 2010; Nitsche et al., 2008).

Second, although there is a high correlation between the trait and state ruminations (Marchetti et al., 2018b), uncertainty remains regarding the respective tDCS' impact on those two constructs. Future research is thus needed to elucidate this issue: (1) by investigating state and trait rumination in single session tDCS studies; and (2), even more importantly, by conducting longitudinal studies of repeated tDCS sessions in order to address the current gaps in this literature. One may also wonder whether trait rumination moderates tDCS' impact on state rumination. Three of the included studies measured both trait and state rumination, but only one (Vanderhasselt et al., 2013) formally tested this hypothesis. They found that trait rumination did moderate the mediation effect (i.e., the higher the trait rumination, the better the improvement on working memory performance induced by tDCS, and the less they ruminated). Thus, future iterations would want to examine whether this moderated mediational effect remains at varying tDCS parameters and samples.

In conclusion, the results of the present systematic review are not definitive. Instead, they set the scene up for the field's larger, ongoing effort to modifying transdiagnostic mechanisms like rumination via brain stimulation techniques. However, because this is the first systematic review of the impact of tDCS on rumination, we also discussed the methodological caveats of this research field to help usher the field forward. From these caveats, we have formulated the following methodological guidelines for future iterations[1] by researchers: (a) embrace open science practices (i.e., more transparency regarding the randomization; pre-registration; and data sharing), (b) use larger sample sizes to increase statistical power, (c) favor the use of protocols and parameters from past studies (unless authors have strong reasons to do otherwise) to ease cumulative science, (d) uncover the best tDCS protocol in general and for particular outcomes (e) and, recruit clinical samples. Like other systematic reviews on emerging research fields, ours fulfills a valuable niche wherein identifying strengths and limitations provides critical clues for larger, more definitive future efforts.

[1] To ease the reporting of future tDCS studies on rumination, we also created a checklist that includes all the relevant features discussed in this systematic review. We believe that adopting such a checklist may help usher the reproducibility and research quality of this field forward. The checklist is available on the Open Science Framework (https://osf.io/hzkgt/).

Chapter 12.

No impact of tDCS on stress-induced state rumination and no influence of executive control and trait rumination: a double-blind sham-controlled within-subjects study

Background. Rumination is conceptualized as a critical transdiagnostic vulnerability and maintenance factor for affective dysregulation and related emotional disorders. Recent research has pointed to transcranial direct current stimulation (tDCS) as a novel therapeutic tool for alleviating rumination, especially stress-induced rumination. However, the mechanisms of action underlying this effect remain unclear, particularly regarding the potential moderating role of executive control and trait-like rumination. Therefore, in this study, we investigated the impact of anodal tDCS on stress-induced rumination and the potential moderating influence of executive control and trait-like rumination in this effect.

Methods. Forty participants from the general community (i.e., unselected sample) took part in a double-blind within-subjects design study wherein we compared anodal stimulation over the left dorsolateral prefrontal cortex (dlPFC) with a sham-stimulation procedure. Participants completed an N-back task, reflecting executive control, during tDCS stimulation, followed by a stress-induction protocol wherein we assessed stress- induced state rumination.

Results. We found no significant effect of tDCS on stress-induced state rumination and no modulation by executive control or trait rumination. Post-hoc Bayesian analyses corroborated these results and even supported the hypothesis that anodal tDCS does not impact stress-induced rumination.

Conclusion. From a clinical perspective, our results are at odds with the current outlook that tDCS is a viable tool for reducing rumination, particularly stress-induced rumination. However, we firmly believe that the results of null-finding studies, such as those from this study, are particularly valuable for future iterations and meta-research on tDCS as a potential tool for targeting transdiagnostic processes, such as rumination. We also addressed methodological limitations and directions for future research in this area.

Reference

Hoebeke, Y., Vanderhasselt, M.-A., Carême, M., Maurage, P., & Heeren, A. (2024). No impact of tDCS on stress-induced state rumination and no influence of executive control and trait rumination: A double-blind sham-controlled within-subjects study. *Clinical Neuropsychiatry, 21(1), 99–109.* https://doi.org/10.36131/cnfioritieditore20240107

12.1 Introduction

Rumination is characterized by negative repetitive thoughts about one's concerns and their causes, meanings, and consequences, without taking action to resolve them (Nolen-Hoeksema et al., 2008). It is considered a transdiagnostic feature of various mental disorders (McLaughlin & Nolen-Hoeksema, 2011a; Watkins, 2015a), and is implicated in their maintenance (e.g., depression, anxiety, binge eating, and substance use disorders). Given its clinical relevance, researchers have sought to gain a deeper understanding of rumination and find ways to reduce it.

Prominent cognitive models postulate that executive control impairments contribute to rumination (e.g., Koster et al., 2011; Watkins & Roberts, 2020). They postulate that deficits in executive control lead to difficulty disengaging from thoughts or shifting attention to other thoughts, resulting in persistent rumination. Cross-sectional studies support this hypothesis, showing associations between rumination and poor executive control at behavioral (Zetsche et al., 2018) and brain levels (Kühn et al., 2014; Vanderhasselt et al., 2011). However, the exact nature and direction of this relationship remain unclear: whereas experimental studies suggest that improving executive control can reduce trait-like rumination (Zwalmen et al., 2023), stress-induced state rumination conversely alters executive control (Philippot & Brutoux, 2008).

Taking stock of this growing literature, researchers applied techniques such as transcranial direct current stimulation (tDCS) to investigate the causal links between rumination and executive control. Indeed, tDCS is a noninvasive brain neuromodulation technique that affects cognitive and motor domains by modulating cortical excitability (Fregni & Pascual-Leone, 2007). Systematic reviews and meta-analyses have demonstrated the safety and therapeutic efficacy of tDCS for various mental disorders (Borrione et al., 2018; Stein et al., 2020; Zortea et al., 2019). Researchers have also successfully achieved the modulation of executive control (Strobach & Antonenko, 2017) and working memory (Brunoni & Vanderhasselt, 2014) in healthy populations by stimulating the dorsolateral prefrontal cortex (dlPFC), a region involved in executive control (Barbey, Colom, et al., 2013; Barbey, Koenigs, et al., 2013; Brosnan & Wiegand, 2017) and rumination (Cooney et al., 2010).

Given the involvement of the dlPFC in executive control and rumination, researchers have started investigating whether tDCS can modulate rumination by stimulating the dlPFC (e.g., De Raedt et al., 2017; Vanderhasselt et al., 2013). In a recent systematic review, five of the nine identified studies showed a significant effect of tDCS on rumination (Hoebeke et al., 2021). Four of these studies found a significant effect of a single tDCS session on state rumination, while one reported a significant effect of ten tDCS sessions on trait rumination (Movahed et al., 2018). However, Hoebeke et al. (2021) identified that between-study heterogeneity was high, especially in terms of stimulation parameters and experimental settings, thus precluding any conclusion that one can draw on the impact of tDCS on rumination.

In addition, the mechanisms underlying the effect of tDCS on rumination remain unclear and require further investigation. The prevailing hypothesis suggests that anodal tDCS applied over the dlPFC can increase the cortical excitability of a neural network involved in executive control, thereby assumedly enhancing executive control, which in turn would reduce rumination (e.g., Koster et al., 2011; De Raedt et al., 2017). Moreover, trait rumination might modulate this mediation effect. Participants with a higher tendency to ruminate have, on average, poorer executive control and might therefore benefit more from the tDCS-induced executive control improvement. However, this hypothesis of moderated mediation—i.e., tDCS impacts state rumination via the improvement of executive control (mediating variable) only among those exhibiting a general tendency to ruminate (moderating variable)—has only been tested and found in one study (Vanderhasselt et al., 2013), leaving open the question of whether changes in executive control serve as a mechanism whereby tDCS influences rumination.

Previous studies also considered rumination as a single, latent entity by using a unique, global scale-score value of rumination (Bernstein et al., 2017, 2020; Hoebeke et al., 2022, 2023a). However, as stated elsewhere (e.g., Bernstein et al., 2017; Hoebeke et al., 2022, 2023a), such a procedure obscures information about the features of rumination. Indeed, several theoretical approaches have suggested that state rumination encompasses several key features. For instance, according to Nolen-Hoeksema's prominent approach (e.g., Nolen-Hoeksema, 1991; Nolen-Hoeksema et al., 2008), state rumination involves five key features, namely *perseveration* (i.e., the time spent thinking about emotional experiences); *negativity* (i.e., to what extent one's thoughts are negative); *self-criticism* (i.e., having self-critical thoughts); *brooding* (i.e., thinking of the causes and consequences of emotional experiences); and *replaying* (i.e., mentally reviewing parts of emotional experiences). And, empirical research capitalizing on this five-feature approach to state rumination has shown the importance of distinguishing these features (Bernstein et al., 2017, 2020; Hoebeke et al., 2022, 2023a), notably with recent works emphasizing the pivotal role of negativity in the emergence of state rumination (Hoebeke et al., 2023a). A critical next step in tDCS research on state rumination will thus be to examine whether tDCS equally impacts the different features of state rumination.

There are therefore gaps in the literature on the effect of tDCS on rumination at three levels. First, it is unclear how tDCS can influence state rumination. The main hypothesis is that changes in executive control mediate this effect, but only one study has examined this mediating role (i.e., Vanderhasselt et al., 2013). Second, the effect of tDCS on state rumination may depend upon the level of trait rumination, as assessed before the stimulation. In other words, this effect may only occur in individuals already exhibiting a general tendency to ruminate. Third, it is unknown whether these effects equally occur across five hallmark features of state rumination. We addressed all these questions in a double-blind, sham-controlled within-subject study design by examining the impact of anodal tDCS applied over the left dlPFC during an executive control task (i.e., an N-back task), on stress-induced state rumination (as in previous research) and by also assessing trait rumination to examine its potential moderating influence.

We hypothesized that anodal tDCS would reduce state rumination, as compared to sham stimulation, and that trait rumination would moderate this effect (i.e., higher trait rumination would be associated with a greater tDCS-induced reduction in executive control and state rumination). Furthermore, similar to previous research (Vanderhasselt et al., 2013), we hypothesized that tDCS-induced executive control improvements (here, the N-back task performance) would mediate the effect of tDCS on state rumination and that the trait rumination would moderate this mediation effect. Finally, we hypothesized that these effects might vary across the five features of state rumination discussed above.

12.2Methods

12.2.1 Transparency and Openness

We provide the de-identified data, R code, and supplementary materials sections at https://osf.io/yq8j5/.

12.2.2 Participants

We recruited an unselected sample of 40 participants (77.5% female) via social media as part of a larger data collection. Participants had a mean age of 21.2 years (SD=2.03) and an average of 9.18 (SD=1.72) years of formal education (after elementary school). All but two participants were students (i.e., one was self-employed, and one was employed). To be included in the study, participants had to be between 18 and 60 years old, be exclusively right-handed, speak French, not be pregnant, not have had neurosurgery, not have neurological problems, not have any signs of epilepsy (or family history of epilepsy), and not have chronic migraines, metallic implants in the brain or face, sensitive skin, or ventricular or cerebral drainage (Antal et al., 2017). The project received the approval of the biomedical review board of UCLouvain (REF# 2020/057) and was conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent. Participants received €50 for participating in the entire study.

12.2.3 Materials and measures

Trait rumination

Participants completed the French-validated version of the Ruminative Response Scale questionnaire (Douilliez et al., 2018) before the two tDCS sessions. The short RRS (RRS-10) is a 10-item self-report questionnaire measuring the tendency to ruminate in response to a negative affect or mood (Treynor et al., 2003). The items are scored on a 4-point Likert-scale from 0 (never) to 3 (always). The 10 items of the RRS-10 showed good internal reliability (α=.77).

Measures of depression and anxiety

To better describe our community sample, we administered the Beck Depression Inventory (Beck et al., 1996) and the Generalized Anxiety Disorder scale (Spitzer et al., 2006). The BDI-II is a 21-item scale assessing symptoms of depression and the GAD-7 is a seven-item scale assessing generalized anxiety disorders symptomatology. We used the validated French versions of the scales (BDI-II; Beck et al., 1996; GAD-7; Micoulaud-Franchi et al., 2016). Both the GAD-7 (α=.76) and the BDI-II (α=.81) showed good internal reliability in the present sample. Table 18 presents the descriptive statistics of these measures.

State rumination

We assessed state rumination as in Bernstein et al. (2017, 2020), who evaluated the five feature of rumination via a specific item based on Nolen-Hoeksema's approach to rumination (Nolen-Hoeksema et al., 2008): "perseveration" (i.e., how much they had been thinking about their performance), "negativity" (i.e., how negative their thoughts were), "self-criticism" (i.e., how much they had been criticizing themselves), "brooding" (i.e., how much they thought about their negative emotional experience), and "replaying" (i.e., to what extent they replayed parts of what happened in their mind). Participants were asked to answer these items in relation to their thoughts during the 5-minute rest period and had to indicate their answers on a scale from 0 to 100 (converted into a score from 0 to 1 with two decimals). In line with recent research on state-like psychological constructs (e.g., Blanchard et al., 2023; Contreras et al., 2024), the order of the items was randomized to prevent systematic sequence effects from introducing bias to the data.

Assessment of Stress

The participants had to indicate three times on a scale from 0 to 100 how tense and calm they felt in response to the stressor: before the tDCS stimulation, after the tDCS stimulation, and after the rest period.

Executive control

We used an N-back task (Owen et al., 2005) with three difficulty levels. On each trial, participants had to indicate whether the stimulus presented was the same as the one presented n trials earlier. They had to click on the left mouse button if the stimulus had been presented n trials previously and on the right mouse button if it had not been presented n trials previously. On each trial, a fixation cross was presented for 700ms, then the stimulus (a capital letter) was presented for 2s, followed by a black dot for 500ms (i.e., in the practice version of the task, feedback was shown for 500ms to indicate whether the response was correct or incorrect, with a green or red dot). During tDCS stimulation, participants performed four 1-back blocks, seven 2-back blocks, and seven 3-back blocks. Each block comprised 25 trials, five of which were targets (randomized). Before tDCS stimulation, participants performed a practice version of the N-back task with one block for each difficulty level (1-2-3) under close supervision of the experimenter to ensure a correct understanding of the instructions. To analyze performance on the N-back task for each difficulty level, we calculated the average reaction time and the discriminability index *d'*, as recommended by Haatveit et al. (2010). *d'* was calculated using the R package "psycho" (Makowski, 2018). The discriminability index represents how well the participant maximizes their hit rate (i.e., the proportion of target stimuli that are correctly identified) and minimizes their false-alarm rate (i.e., the proportion of non-target stimuli that are incorrectly identified as targets): the higher the *d'*, the better the participant can discriminate target from non-target when performing a task. The discriminability index is a useful measure because it considers both the accuracy and the response bias of the person (Haatveit et al., 2010). We adjusted extreme values following the recommendations of Hautus (1995) and coded the task in OpenSesame V3.3.6 (Mathôt et al., 2012).

12.2.4 Stress induction

Following Bernstein et al. (2017), we used a serial subtraction task to induce stress. In this task, participants had to count backward as fast as possible for three minutes (i.e., start at 572 and then subtract 13 each time). Participants had to start over if they were too slow (i.e., took more than three seconds to answer) or made a mistake, in which cases the experimenter said, "Too slow" or "Error." This task was designed to put participants under pressure and elicit rumination in a subsequent five-minute rest period in which they were asked to sit still and do nothing. Supplementary Material (Section 3) gives more details regarding the manipulation check.

12.2.5 tDCS

Direct electrical current was delivered via a NeuroConn DC-Stimulator Plus device, with integrated "double-blind study mode" (Neuroconn, GmbH, Ilmenau, Germany) and applied via a pair of sponge rubber electrodes ($35cm^2$) soaked in saline (i.e., 0.9% NaCl concentration). We used a sham-controlled within-subjects design so that all participants served as their own control. We placed the anode electrode vertically and centered over F3, according to the international 10–20 system for electroencephalogram electrode placement, to stimulate the left dlPFC. As in prior research (e.g., Heeren et al., 2015; Vanderhasselt et al., 2013), we placed the cathode electrode horizontally on the right supraorbital area. A constant direct current of 2mA, starting with 30 s ramp-up, was applied for 20 minutes, with 30 s ramp down at the end.

During sham stimulation, we placed the electrodes in the same location. However, the current ramped down to 0 mA after the first 30 s. This procedure is commonly used in tDCS research and is an optimal method to convey the initial sensations of the effects of the stimulation on cortical excitability (Nitsche et al., 2008). We used predefined codes assigned to either sham or real stimulation to start the stimulator, allowing for a double-blind study design. We randomized and counterbalanced the order of anodal and sham stimulations between participants. The stimulation started 5 minutes before the N-back task and lasted for a period of 20 minutes (see procedure in the next section). Thus, the N-back task was performed simultaneously with the stimulation. Finally, the second stimulation was performed one week later (if possible, at the same time of day) to avoid carry-over effects.

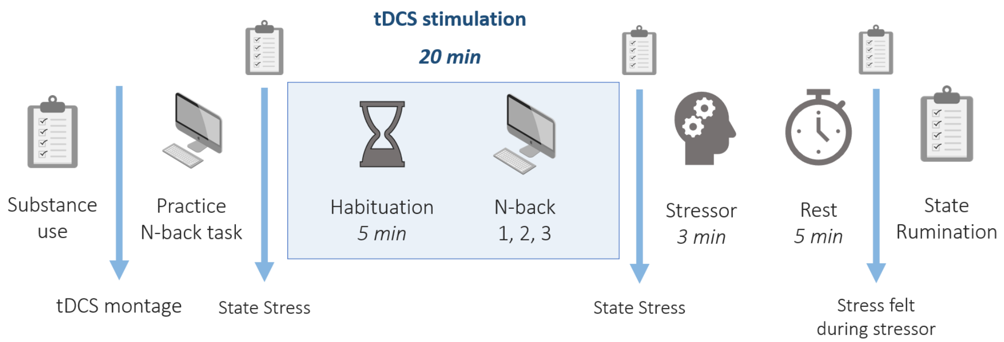
12.2.6 General Procedure

Before coming to the laboratory sessions, each participant received a link to an online form, wherein they provided all the information relevant for a first general assessment of the exclusion criteria and the general demographic information. Participants completed the RRS-10, GAD-7, and BDI-II via this online assessment.

When arriving at the laboratory session, the instructor carefully checked once again all the inclusion and exclusion criteria, and participants completed questionnaires on substance use.

After installing the electrodes, a practice version of the N-back task was conducted. After this task, the participants indicated how tense versus calm they were from 0 (“*Calm*”) to 100 (“*Tense*”). The anodal stimulation, or sham stimulation, began 5 minutes before the start of the N-back task and was carried out for 15 minutes. After completion of the N-back task and tDCS stimulation, we removed the tDCS, and participants again indicated how tense/calm they felt. Next, participants underwent a stress induction. They then had a five-minute rest period, during which they were asked to sit still and do nothing. After this rest period, participants completed a state measure of rumination and indicated how tense/calm they felt during the serial subtraction task. At the end of the second tDCS session, participants completed a questionnaire adapted and translated from Antal et al (2017) to assess tDCS side effects, sensations (see Supplementary Materials), and blinding. To assess blinding, participants indicated for each session whether they believed they were receiving real stimulation or sham stimulation, or whether they did not know which stimulation they had received (Antal et al., 2017). Importantly, participants were informed that they received real stimulation twice to obtain more consistent measures, and we did not disclose the true aim of the study until the end of the second session, after the questionnaires. Figure 26 provides an overview of the procedure.

Figure 26. Study protocol



12.2.7 Data analysis plan

We computed linear mixed models and Bayesian analyses using R, version 4.2.2 (R Core Team, 2022). Each analysis was performed accounting for time and order effects. We fitted linear mixed models estimated with REML, type 3 sum of squares, and Satterthwaite’s degrees of freedom (Luke, 2017). We used the R package ‘DHARMa’ to check the assumptions of the mixed models (Hartig, 2022). For all models, we calculated the conditional R^2 (considering both fixed and random effects) and the marginal R^2 (considering only fixed effects) using the method of Nakagawa et al. (2017) as implemented in the R package ‘performance’ (Lüdecke et al., 2021). Following recent guidelines (Biel & Friedrich, 2018), we also computed Bayesian mixed models using Bayesian statistics with the R package ‘BayesFactor’ (Morey & Rouder, 2022) to further test the effect of tDCS on rumination and N-back performance. To do so, we used Bayesian model averaging and report the posterior inclusion probability for each predictor for each dependent variable (Hinne et al., 2020). When reporting the results of the post-hoc Bayesian analyses, we used Jeffrey's guidelines to interpret the Bayes factors (Jeffreys, 1998; Wetzels et al., 2011), translating the value of the Bayes factor into a qualitative judgement of the level of evidence (i.e., "Barely worth mentioning"; "Substantial"; "Strong"; "Very Strong"; "Decisive"). Finally, we performed moderated mediation analyses in SPSS using the macro MEMORE (Montoya, 2019).

12.3 Results

We removed one participant from the analysis because data from one session was missing due to a technical error. We also removed five participants who correctly guessed the type of stimulation in both sessions, which can bias the results (Supplementary Materials, Section 4). Table 18 shows the descriptive statistics of all our variables of interest.

Table 18. Descriptive statistics

	observations	*mean*	*SD*	*median*	*min*	*max*	*range*
RRS-10	40	10.38	5.09	11	1	22	0–30
BDI-II	40	11.8	6.9	11	1	34	0–63
GAD-7	40	6.25	3.81	6.5	0	16	0–21
Age	40	21.2	2.03	21.5	18	26	
Years of studies	40	9.18	1.72	9.5	6	12	
d' 1-back	78	3.9	0.52	3.97	2.77	4.48	
d' 2-back	78	3.6	0.62	3.6	2.21	4.89	
d' 3-back	78	2.78	0.56	2.77	1.29	4.03	
RT 1-back	78	540.32	97.25	541.40	364.52	771.57	
RT 2-back	78	673.99	151.89	665.38	387.36	1231.61	
RT 3-back	78	726.67	163.36	708.34	394.78	1218.22	
Total Rumination	78	2.17	1.03	2.16	0.1	4.31	0–5
Brooding	78	0.41	0.27	0.35	0.00	1	0–1
Negativity	78	0.32	0.25	0.26	0.00	0.8	0–1
Replaying	78	0.48	0.28	0.55	0.01	0.97	0–1
Self-criticism	78	0.42	0.26	0.4	0.00	0.9	0–1
Perseveration	78	0.53	0.27	0.58	0.00	0.98	0–1

Note. GAD-7 = general anxiety disorders symptoms; BDI-II = depression symptoms; RRS-10 = comprises the brooding and the reflection subscales of the Ruminative Response Scale. Years of studies = completed years of formal education after high school. The minimum and maximum correspond to the minimum and maximum score observed in our sample. The range represents the possible scores for each questionnaire.

12.3.1 Effects of tDCS on Rumination

There was no significant effect of tDCS on state rumination, neither at the total scale score nor at the level of its distinctive features (all *ps*>.05), controlling for session and stimulation order. Likewise, the interaction between 'tDCS condition' and 'trait rumination' had no significant effect on state rumination, neither at the total scale score nor at the level of its distinctive features (Table 19). Regarding our third hypothesis about the role of the different features of rumination, there was no significant effect.

Table 19. Linear Mixed models of total state rumination and features of rumination

	Total State Rumination				Negativity				Brooding				Replaying				Self-Criticism				Perseveration			
Predictors	***B***	***SE***	***t(31)***	***p***	***B***	***SE***	***t(31)***	***p***	***B***	***SE***	***t(31)***	***p***	***B***	***SE***	***t(31)***	***p***	***B***	***SE***	***t(31)***	***p***	***B***	***SE***	***t(62)***	***p***
(Intercept)	2.08	0.12	17.49	<0.001	0.31	0.03	8.87	<0.001	0.38	0.03	12.78	<0.001	0.46	0.03	13.41	<0.001	0.41	0.03	11.9	<0.001	0.51	0.03	17.7	<0.001
Stimulation order	0.1	0.13	0.78	0.442	0.01	0.04	0.31	0.755	0.02	0.03	0.54	0.596	0	0.04	0.04	0.972	0.01	0.04	0.38	0.707	0.05	0.03	1.76	0.083
Session	0.47	0.11	4.3	<0.001	0.04	0.02	1.72	0.095	0.09	0.03	3.09	0.004	0.12	0.03	4.11	<0.001	0.08	0.03	2.94	0.006	0.14	0.03	4.61	<0.001
Condition	-0.14	0.1	-1.35	0.188	-0.04	0.02	-2.01	0.053	-0.03	0.03	-0.94	0.353	-0.02	0.03	-0.89	0.379	-0.03	0.02	-1.15	0.258	-0.02	0.03	-0.61	0.543
RRS-10	0.04	0.02	1.74	0.091	0.02	0.01	2.26	0.031	0.02	0.01	2.88	0.007	0	0.01	-0.36	0.723	0.01	0.01	1.35	0.187	0	0.01	0.26	0.793
Condition × RRS-10	0	0.02	0.12	0.904	0	0	-0.27	0.788	0	0.01	-0.4	0.694	0	0.01	0.33	0.742	0	0	0.74	0.462	0	0.01	0.08	0.94
Marginal R^2 / Conditional R^2	0.252 / 0.357				0.151 / 0.561				0.239 / 0.277				0.182 / 0.360				0.120 / 0.409				0.289 / NA[a]			

Note. N = 34; Observations = 68; Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first); RRS-10 = trait rumination (mean-centered).

[a]The model had a singular fit; random effects were estimated as being null.

12.3.2 Effects of tDCS on executive control

We tested the effect of tDCS on N-back performance before performing the full mediation analysis in SPSS. We only report the results of the 3-back task, as this was the most difficult task, considering that tDCS may have a greater effect on more difficult tasks (Papazova et al., 2020). We verified this assumption: the condition (anodal vs sham tDCS) did not influence 1-back and 2-back reaction times or *d'* prime (Supplementary Materials, Table S2).

After checking for outliers, we removed two participants for the 3-back reaction time analyses and three participants for the *d'* analyses. TDCS significantly affected 3-back reaction times (i.e., slower reaction times in the anodal stimulation condition, $t(1,29)=2.25$, $p=0.032$, but not *d'*, $t(1,28)=0.43$, $p=0.674$, controlling for session and stimulation order). The effect of session on RT and *d'* was significant (RT: $t(1,29)=8.41$, $p<.001$; *d'*: $t(1,28)=2.94$, $p=0.007$), indicating faster reaction times in the second session. The main effect of trait rumination and the interaction effect between the condition and trait rumination were not significant for *d'* or 3-back RT (see Table 20).

Table 20. Linear Mixed models of d' and reaction time on the 3-back task

	***d'* 3-back**				***RT* 3-back (log transformed)**			
Predictors	***B***	***SE***	***t(28)***	***p***	***B***	***SE***	***t(29)***	***p***
(Intercept)	2.75	0.06	44.26	<0.001	2.84	0.01	228.4	<0.001
Stimulation order	-0.1	0.07	-1.48	0.15	0.02	0.01	1.43	0.163
Session	-0.18	0.06	-2.94	0.007	0.04	0.01	8.41	<0.001
Condition	-0.02	0.06	-0.43	0.674	-0.01	0	-2.25	0.032
RRS-10	-0.02	0.01	-1.36	0.186	0	0	0.28	0.783
Condition × RRS-10	0	0.01	-0.1	0.924	0	0	-0.52	0.609
N	31				32			
Observations	62				64			
Marginal R^2 / Conditional R^2	0.176 / 0.261				0.300 / 0.809			

Note. Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first; RRS-10 = trait rumination (mean-centered).

12.3.3 Moderated Mediation

Although none of our main effects were significant, we decided to run the moderated mediation model exploratory, using the MEMORE macro for SPSS with trait rumination as the centered moderator variable and the reaction times of the 3-back task as the mediator variable. The moderated mediation was not significant, neither at the total scale score nor at the level of its distinctive key features. Interestingly, 3-back RT positively predicted total state rumination scores and also the scores of the individual features of rumination except for negativity (see Supplementary Materials, Tables S3-S8, for the full results of the mediation analysis for each variable).

12.3.4 Additional Exploratory Analyses

The absence of a direct effect of tDCS on rumination combined with the significant prediction of rumination only by 3-back RT task in the mediation analysis prompted us to further investigate the relationship between the 'N-back task' and 'rumination'. To this end, we conducted post-hoc exploratory analyses in which we included 3-back task RT as a predictor in mixed models. In addition to this, we wanted to determine whether it was possible that participants were ruminating about their performance on the N-back task and not about their performance on the backward counting task. Although we did not explicitly ask participants what they ruminated about during the resting period, we indirectly tested this hypothesis by including the stress score related to stress induction in the analyses.

For brevity, the full results are presented in the Supplemental Material (Section 7). The full model, which includes the stress score and 3-back RT, explained 33.5% of the variance in total state rumination (Table S9). The main effect of 3-back RT was significant ($t(1,36.09)=2.58$, $p=.014$), but not the effect of stress ($t(1,53.8)=1.74$, $p=0.096$). These results suggest that slower reaction times during the N-back were associated with higher total state rumination (faster reaction time [-1SD=565 ms]=1.76/5 total state rumination; slower reaction time [+1SD=842ms]=2.46/5 total state rumination). For the features of rumination, the results were mixed: brooding was significantly predicted by RT whereas perseveration and replaying were predicted by stress. In contrast, negativity and self-criticism were predicted by neither stress nor RT. Moreover, we found the same pattern of findings as in our first analyses (see Table 19): a considerable proportion of the variance of negativity and self-criticism was explained by random effects and only a tiny proportion was explained by fixed effects, as shown by the difference between marginal and conditional R^2 (Supplementary Material, Section 7, Tables S10–S14).

12.3.5 Bayesian analyses

We used Bayesian analyses to further test the effect of tDCS on state rumination and the 3-back task. Table 21 shows the results of the Bayesian model averaging procedure of Bayesian mixed models with participants as the random variable, condition, session, trait rumination, 3-back RT, and stress after the stress induction as predictors, always accounting for at least 'session' as a predictor, with the denominator being a null model. The inclusion Bayes factors reported hereafter indicate how much more likely the observed data is under a model with a term compared to a model without this term.

First, contrary to our hypotheses, there was substantial evidence indicating that neither the condition (active vs sham tDCS) nor the interaction between condition and trait rumination explained the observed data for total rumination and d' prime (all BFs≤.33). The evidence regarding the effect of condition on 3-back RT was inconclusive. Moreover, there was a decisive level of evidence for the inclusion of 'participants' as a random factor in predicting of 3-back RT with a Bayes factor of 12456.97. This suggests that there are significant individual differences in 3-back RT that are not accounted for by the fixed effects in the model. However, there was considerable evidence against the inclusion of 'participants' (i.e., the random effect) as a predictor of total state rumination and 3-back d', with Bayes factors of 0.21 and 0.32, respectively, suggesting individual differences beyond the fixed effects included in the model played a lesser role in these outcomes. Finally, there was strong evidence for 3-back RT as a predictor of total rumination (BF=13.29), but no evidence for or against the effect of stress on rumination (BF=1.12). We also examined this effect on the five key features of rumination and found substantial evidence that tDCS had no impact on the features (all BFs≤.33), apart from negativity (anecdotal evidence for H0: BF=.52). More details regarding these analyses are provided in the Supplementary Materials (see Section 8).

Table 21. Inclusion Bayesian Factors for total state rumination, rumination features, and 3-back performance

		Total Rumination		***d'* 3-back**		***RT* 3-back**	
Predictor	**prior P()**	**post. P()**	**Incl. BF**	**post. P()**	**Incl. BF**	**post. P()**	**Incl. BF**
Condition	0.6	0.25	0.23	0.24	0.21	0.68	1.42
RRS-10	0.6	0.58	0.91	0.31	0.3	0.38	0.41
Session	0.5	0.67	2.02	0.94	15.95	1.00	7E+06
ID	0.5	0.12	0.13	0.20	0.25	1.00	12457
3-back RT	0.5	0.93	13.29				
Stress during stressor	0.5	0.53	1.13				
Condition*RRS-10	0.2	0.04	0.18	0.03	0.11	0.09	0.37
Stimulation order	0.5	0.23	0.3	0.33	0.49	0.46	0.86

Note. Incl. BF = indicates how much more likely the observed data is under a model with this term compared to a model without this term; prior P() = prior probabilities; post. P() = posterior (inclusion) probabilities (i.e., the model-average probability of including a certain predictor in the model, given the observations); Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first); RRS-10 = trait rumination (mean-centered). Inclusion bayes factors higher than 3 (i.e., substantial evidence for including this term in the model) and lower than 1/3 (i.e., substantial evidence against including this term in the model) are in bold.

12.4 Discussion

We investigated the effect of tDCS on rumination. We postulated that anodal tDCS stimulation over the left dlPFC would decrease state rumination, with trait rumination moderating this effect. We predicted that the N-back task performance would mediate the impact of anodal tDCS on state rumination, with trait rumination moderating it. Moreover, we expected that these effects would vary across five features of state rumination (i.e., perseveration, replaying, brooding, negativity, self-criticism). Yet, none of our predictions were confirmed. Instead, post-hoc Bayesian analyses even lent strong credence to the null hypothesis: tDCS has no impact on stress-induced state rumination.

One possible explanation for this lack of effect is that, in contrast to previous studies (Brunoni & Vanderhasselt, 2014; Strobach & Antonenko, 2017, but see Coussement et al., 2019, 2020), we did not improve executive control during anodal tDCS. However, relying upon a community sample might have resulted in a ceiling effect in executive control, making it difficult to observe improvements with tDCS (Coussement et al., 2019, 2020). There is even research suggesting that tDCS may disrupt efficient processing in healthy participants by interfering with optimal neural homeostasis (Habich et al., 2020). This disruption could explain why active tDCS tended to slow reaction times in the 3-back block of the N-back task; an observation consistent with previous research in healthy samples (de Boer et al., 2021).

These points raise further questions about the effects of tDCS on rumination and its mechanisms. How can we reconcile our results with studies demonstrating tDCS effects in healthy participants? Sources of variability, such as individual cortical thickness and electric field magnitude, could account for these differences. For instance, thinner cortical thickness (Razza et al., 2022) and higher electric field magnitudes (Razza et al., 2023) of the dlPFC predicted faster N-back reaction times during tDCS. Furthermore, differences in outcomes could be due to differences in executive control abilities of the participants in the different 'healthy' samples. Future research should examine these sources of variability or directly assess participants' executive control abilities. But, in any case, perhaps the most striking implication of the present study is that, from a clinical perspective, the current results, and particularly those resulting from the post-hoc Bayesian analyses, suggest that tDCS is not yet ready to be considered a viable clinical tool for alleviating rumination. As discussed in detail elsewhere (i.e., Hoebeke et al., 2021), more robust and stable findings across different contexts, cultures, and clinical populations need to be established before the prospect of tDCS as a viable promise for the mitigation of rumination in clinical practice can be considered.

Our findings have two additional implications, which are critical for future research iterations on the impact of tDCS on state rumination. Based on the results of our mixed regression models, we identified distinct patterns in content-related versus process-related features of rumination — to dovetail with the Ehring and Watkins (2008)'s proposal that features of rumination can either be tapping into content-related or process-related aspects. Specifically, we found that the variance of content-related features, such as negativity and self-criticism, was primarily accounted by random effects, which explained 25-30% of the variance. This indicates that individual differences play a significant role in these features — a view consistent with existing research on negative affectivity (D. Watson & Clark, 1984) and self-criticism (Schanche, 2013; Zuroff et al., 2016) as persistent traits. Conversely, the variance of process-related features (i.e., replaying, brooding, and perseveration) was mostly accounted by fixed effects, which explained 30-36% of the variance. This implies that the variability in these process-related features is more influenced by the predictors incorporated into our model than by individual differences. Overall, our findings underscore the necessity of differentiating between content and process aspects in rumination research to fully capture this multifaceted construct. Future studies could therefore focus on measuring only process-related features of rumination.

The second implication concerns the potential consequences of the 3-back RT on stress. Indeed, our results suggest that 3-back RT predicted total state rumination, even when controlling for stress induced by the serial subtraction task. There are two possible explanations for the fact that N-back RT significantly predicted total state rumination. One possibility is that slower reaction times in the N-back task are associated with limited cognitive resources.

Consequently, they were less able to inhibit their thoughts and ruminated more during the rest period. An alternative explanation could therefore be that the N-back task was stressful (perhaps even more stressful than the serial subtraction task) and that participants reflected on it during the rest period, especially if they performed poorly (i.e., longer reaction times) on the 3-back task. Considering that the experience of failure can lead to rumination (Koole et al., 1996; van der Kaap-Deeder et al., 2016; Watkins, 2004), the stress induced by highly-demanding computerized cognitive tasks, especially when particularly cognitively demanding, could alter tDCS effects.

Our study has several limitations. First, the tDCS montage used here, although common in studies examining the impact of tDCS on rumination (for a review, see Hoebeke et al., 2021), might not optimally influence rumination. Simulation studies suggest that different montage configurations could affect different parts of the prefrontal cortex, not just the dlPFC, and alter cortical electric field distributions (Bikson et al., 2010; Soleimani et al., 2021), with the extracephalic montage showing promising results (D. M. Martin et al., 2023; Noetscher et al., 2014). Second, although we used self-report measures of stress, we did not rely upon physiological measures, such as heart rate variability (Shaffer & Ginsberg, 2017) or salivary cortisol (Zoccola et al., 2008). Therefore, uncertainty remains as to whether the stressor indeed elicited a stress response in participants. Finally, participants were tested during the COVID-19 pandemic, and, as such, one cannot exclude that wearing masks and the intensive hands and equipment sanitizing at the beginning of the experiment impact on participants' involvement in the experiment. Likewise, since the COVID-19 pandemic's lockdown and other related social distancing measures have been particularly distressing and sources of respective negative thinking processes, such as rumination and worries (e.g., Heeren et al., 2021; Mertens et al., 2020; Suen et al., 2022), one may wonder about the influence of the pandemic on our participants' reactivity to laboratory-induced stressor.

12.5 Conclusion

In this study, tDCS had no effect on rumination, neither at the level of global scale scores nor at the level of its five hallmark features. Although none of our hypotheses were supported, the present null results will benefit future meta-research in this area. Future research should consider diversifying participant samples, exploring other potential variables, and refining experimental designs to gain a comprehensive understanding of the multilayered interactions at play.

Section 4.

General discussion

Chapter 13.

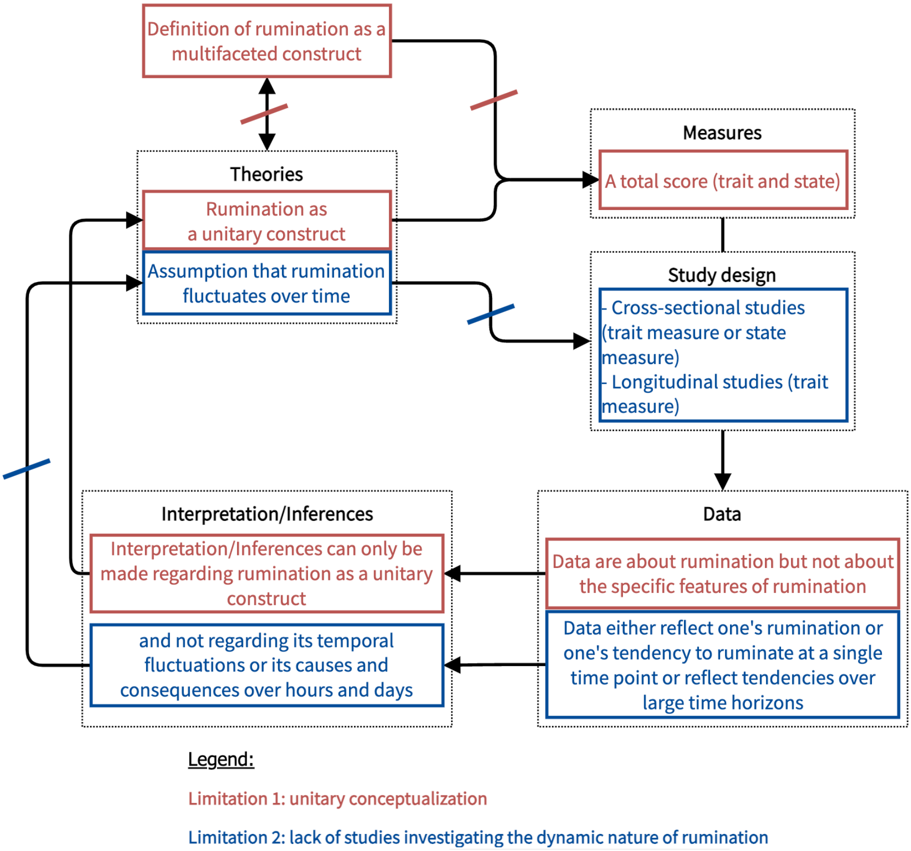
Comparison and integration of the main findings

We all ruminate from time to time. However, some people ruminate more than others, which harms their mental health. Extensive research shows that rumination is implicated in a variety of mental disorders (McLaughlin & Nolen-Hoeksema, 2011a) and is associated with worse health outcomes (e.g., Szabo et al., 2022). Consecutively, given its transdiagnostic nature and influential role in mental health, researchers developed and explored a wide range of theories and hypotheses about how rumination works and how it leads to negative outcomes.

Executive control has emerged as a key mechanism of rumination from this extensive research. On the one hand, some researchers postulated that impaired executive control contributes to rumination, given that people are unable to disengage from their thoughts. On the other hand, other researchers suggested that rumination occupies cognitive resources, thereby impairing executive control. Yet, research surrounding these hypotheses has not been able to clarify the direction of causality between rumination and executive control, as most findings are derived from cross-sectional research and as experimental research led to mixed results.

Therefore, uncertainty still abounds regarding rumination and executive control, despite rich theoretical contributions and extensive research on rumination, its mechanisms and consequences, and its associations with executive control. After reviewing this research literature, we realized that two limitations might be holding back further progress in understanding rumination (see Figure 27). The first limitation relates to how rumination has been conceptualized and measured as a unitary construct, even though it is agreed upon that rumination has distinct characteristics. The second limitation is that, even though rumination is considered a dynamic process, the most commonly used study designs do not measure these temporal fluctuations. We argued that these two limitations constrained research on rumination and, thereby, the inferences researchers could make.

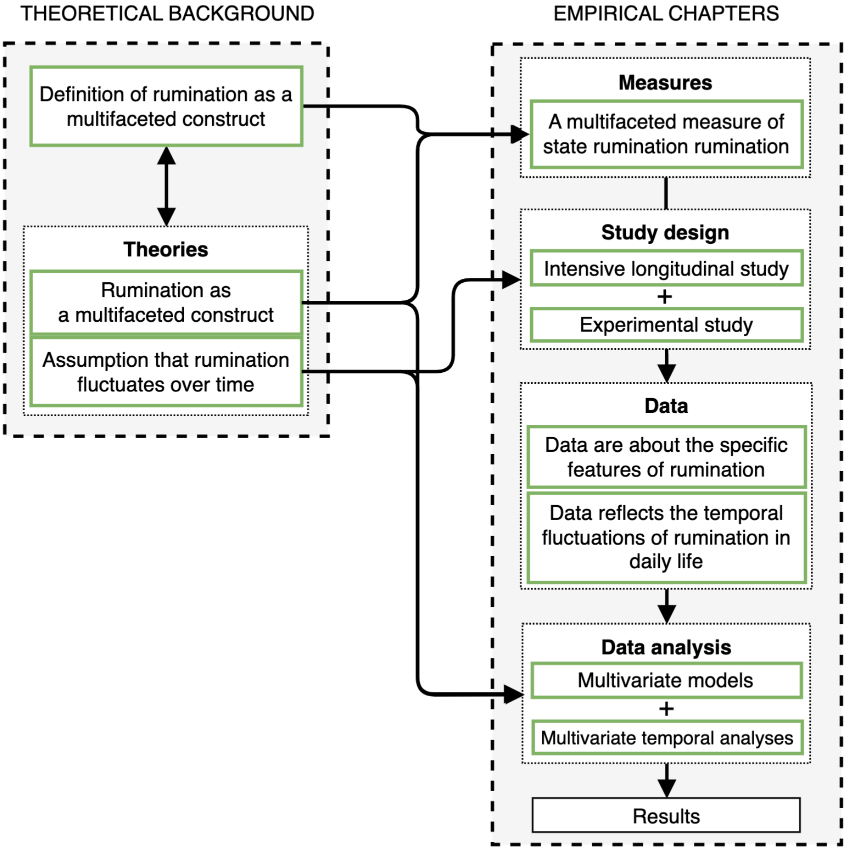
Figure 27. A visual representation of the two main limitations



Note. The first limitation is that theories mainly conceptualize rumination as a unitary construct by not integrating the different features of rumination. This unitary view can constrain hypotheses and is reflected in rumination measures. Consecutively, the collected data and the inferences made about this data only feed the theories in a limited way, given that they do not inform about the role of the different features of rumination. In this way, solely based on this research process, theories do not change as one core assumption (rumination as a unitary construct) is never challenged.
The second limitation is that, even though rumination is considered a dynamic process, the most used study designs do not measure these temporal fluctuations. Consequently, uncertainty remains regarding the temporal fluctuations of rumination over hours and days and how these fluctuations relate to the causes and consequences of rumination. Hence, how rumination is studied, mainly as a static construct, does not provide enough empirical information that could feed into theories; it is in this respect that theoretical development is hindered, as fluctuations of rumination over time and their causes and consequences are not directly investigated.

The goal of this thesis was to address these two limitations in how rumination has been studied so far to better understand rumination and its associations with executive control. To overcome the noted research limitations, we designed a series of studies that reconceptualize rumination as a complex, multifaceted construct, and we used intensive longitudinal methods to capture its temporal dynamics in daily life. In order not to completely start anew, we based ourselves on the multifaceted conceptualization of rumination by Bernstein et al. (2017), which conceptualized rumination as a network system and focused on five features of rumination. Both the dynamic aspect and the multifaceted aspect of rumination were infused in as many parts of the research process as possible: the measurement, the research methods, and the analyses (see Figure 28).

Figure 28. Overview of the thesis



Note. This figure illustrates how the theoretical background chapters emphasized the multifaceted and dynamic nature of rumination. These two aspects were infused in the empirical chapters of this thesis and guided the choice of our research methods and analysis methods.

In this discussion, I will summarize our findings (see Table 22), highlight how they converge and diverge, and integrate them with previous research and prior theories. Importantly, this thesis focused on two main lines of research: (a) studying rumination as a dynamic, multifaceted construct by focusing on five features, and (b) investigating the associations between executive control and rumination as a multifaceted construct. These two lines of research were explored across two different axes: one axis relied on an intensive longitudinal research design, and the other axis approached the same question from an experimental perspective using tDCS (see Table 22 for a summary of the objectives of each chapter and the main findings). This first chapter of the discussion will follow our two main lines of research across both axes, first by discussing our results regarding the multifaceted and dynamic nature of rumination, then by discussing our findings regarding the associations between rumination and executive control. The following chapters will cover the theoretical, methodological, and clinical implications of our studies. Lastly, I reflect on some broader implications for the psychological sciences based on our results and the perspective I developed on research while doing this thesis. Moreover, rather than having a separate section on limitations and future perspectives at the end of the discussion, I systematically highlight the limitations of this thesis in the appropriate sections and suggest future research directions. Ultimately, this discussion and the conclusion will address whether reconceptualizing rumination as a multifaceted and dynamic process did indeed improve our understanding of rumination and its associations with executive control and whether it opened new paths for future research.

Table 22. Summary of objectives and the results of the empirical chapters

Chapter	Objective(s)	Findings
7. An experience sampling measure of the key features of rumination	Develop a multifaceted measure of rumination for intensive longitudinal studies.	• Successfully developed and validated a bilingual (French and English) momentary measure of rumination for intensive longitudinal studies. • Intra-class correlations for all items < 0.4, reflecting adequate within-person variability when measured four times daily. • Observed correlations between rumination features and trait rumination, depressive symptoms, and anxiety symptoms were in the expected directions.
8. Negativity is key for understanding the interplay between rumination's features, attention control, and their dynamic nature: a temporal network approach	1. Investigate the interplay between rumination features and attention control over time, testing the network conceptualization of rumination. 2.Test the impaired disengagement hypothesis and the resource depletion account.	• Results support the network conceptualization with distinct associations among rumination features. • Negativity was identified as a primary driver. It positively predicted all the other features at the next time point. • Between-subject analyses revealed a unique positive association between negativity and self-criticism, and a distinct pattern for replaying with perseveration and brooding. • Findings support the resource depletion account, with negativity consistently predicting lower attention control over time, challenging the impaired disengagement hypothesis.

Chapter	Objective(s)	Findings
		• Conversely, the contemporaneous and between-subjects associations were in line with the impaired disengagement hypothesis: attention control was negatively associated with negativity at the contemporaneous level and was negatively associated with brooding at the between-subjects level.
9. Information theory and time series in psychology: transfer entropy and the case of rumination and attention control	1. Investigate the interplay between rumination features and attention control over time, testing the network conceptualization of rumination. 2.Test the impaired disengagement hypothesis and the resource depletion account. 3. Explore the use of information theoretic multivariate analyses for time series in psychology.	• Negativity and self-criticism predicted perseveration and replaying; these, in turn, influenced attention control, corroborating the resource depletion account but not the impaired disengagement hypothesis. • Multivariate transfer entropy and active information storage analyses suggest negativity and self-criticism as potential stable traits underpinning rumination, influencing subsequent perseveration and replaying.
10. Predicting depression and anxiety from the temporal features of rumination: an affective dynamic approach	1. Investigate the temporal dynamics of features of rumination (inertia and moment-to-moment variability). 2. Investigate the predictive value of metrics derived from ESM-data compared to trait rumination.	• Process-related features (perseveration, brooding, replaying) showed distinct patterns from content-related features (negativity and self-criticism): only the person-level mean of process features had predictive value whereas the variability and inertia of content features had additional predictive value beyond person-level means. • Moment-to-moment variability values strongly correlated with their variability and were excluded from the analyses. • ESM-derived statistics and trait rumination uniquely predicted depression and anxiety; particularly, self-criticism and negativity variability, as well as negativity inertia, emerged as significant predictors of depression.
11. The impact of transcranial Direct Current stimulation on rumination: A systematic review of the sham-controlled studies in healthy and clinical sample	Provide an objective view of the literature on the effects of tDCS on rumination and identify the best combination of tDCS parameters and study design to influence rumination.	• This systematic review yielded inconclusive results due to heterogeneity in study designs and tDCS parameters, alongside mixed outcomes.

Chapter	Objective(s)	Findings
12. The impact of tDCS on stress-induced state rumination: Are executive control and trait rumination really at play?	1. Investigate the effect of tDCS over the dlPFC on rumination, looking at the effect among rumination features 2. Test whether the effect of tDCS on rumination is mediated by executive control and moderated by trait rumination	• There was no significant effect of tDCS on state rumination or its features. • Moderated mediation analysis yielded non-significant results. • Bayesian analyses supported the null hypothesis regarding active tDCS effects on state rumination. • The results revealed a distinct pattern in explained variance: fixed effects accounted for process features, whereas random effects predominated for content feature variance.

13.1 Rumination as a dynamic multifaceted construct

13.1.1 Comparison of our findings

Negativity as a key driving feature of rumination

Our initial objective was to conceptualize and measure rumination as a dynamic, multifaceted construct. The outcomes consistently affirm the validity and utility of this perspective in enhancing our understanding of rumination. As shown in Table 22, a first key observation across our studies is that, among the five features of rumination, the extent to which one's thoughts are negative (i.e., negativity) stands out as the most influential feature of rumination (Ch. 8, 9, 10). It consistently emerged as an influential driver of other rumination features over time (Ch. 8 and 9). In Chapter 8, negativity negatively predicted all other features of rumination at the next time point and predicted poorer executive control at the next time point. In Chapter 9, negativity predicted perseveration within the same time point and was only predicted by self-criticism. Therefore, although negativity was the most influential of the features of rumination across studies, its associations with other features of rumination and executive control varied across methods of analysis. Additionally, the person-level means of content features of rumination (i.e., a composite variable of negativity and self-criticism) significantly predicted depression and anxiety symptoms, controlling for trait rumination and other ESM-derived statistics (Chapter 10). This result further supports the influential role of negativity among the features of rumination.

Moreover, in addition to the person-level mean of content features, negativity inertia[1] and negativity SD also significantly predicted depression symptoms (Chapter 10). This inertia of negativity also showed in transfer entropy analyses. Although the differences in the methods of analysis do not allow a direct comparison of the results, the transfer entropy analyses also suggest

[1] As a reminder, the inertia values used in Chapter 10 were extracted from the mlVAR analysis of Chapter 8.

that past negativity intensity is predictive of future negativity. Hence, two different types of analyses illustrated the self-perpetuating nature of negativity.

In addition to negativity, only brooding showed inertia in Chapter 8. Moreover, in Chapter 10, brooding inertia significantly predicted anxiety symptoms but not depression symptoms when only accounting for ESM data, and it was a marginally significant predictor once trait rumination was included. Yet, contrary to negativity, brooding did not exhibit this inertia in the transfer entropy analyses. Lastly, perseveration and replaying never showed inertia, whereas self-criticism exhibited inertia in the transfer entropy analyses.

The important role of self-criticism

Self-criticism played an influential role in some studies (Chapters 9 and 10) but not others (Chapter 8). In Chapter 9, self-criticism predicted replaying within the same time point and also predicted negativity within the same time point and from one time to the next. In Chapter 10, even after controlling for trait rumination, the person-level means of negativity and self-criticism and the variability of self-criticism predicted depression. This influential role of self-criticism in Chapters 9 and 10 is at odds with the results from Chapter 8, which indicated that negativity was the most influential feature, predicting self-criticism from one time point to the next.

However, one commonality among Chapters 8, 9, and 10 is that self-criticism and negativity seem closely intertwined. In Chapter 8, self-criticism and negativity were strongly positively correlated within the same time point and at the between-subject level. In Chapter 9, self-criticism and negativity predicted each other: self-criticism (current self-criticism and one past lag) predicted negativity; current negativity and 10 past lags of negativity predicted self-criticism. In Chapter 10, the person-level means of negativity and self-criticism showed multicollinearity and had to be combined into a composite variable. Overall, apart from the temporal network in Chapter 8, our results sugget that negativity and self-criticism are closely intertwined and might both be key features of rumination.

Content versus process features

Through all our studies, the results also suggested that the items of negativity and self-criticism, both as a laboratory state measure and as a state measure in daily life, captured or reflected stable trait-like dispositions. In the tDCS study (Chapter 12), negativity and self-criticism were mainly explained by random effects and not fixed effects, as indicated by the R^2 of the mixed models. This stood in sharp contrast to repetitiveness, brooding, and replaying, which were almost only explained by fixed effects. In the transfer entropy study (Chapter 9), negativity and self-criticism had the highest active information storage, and almost all their 19 past lags significantly provided information. This could mean that there is inherent stability to these features of rumination, that they are less context-dependent than the other variables in the network, and that they reflect trait-like dispositions. In contrast, as said previously, the process features had fewer past significant lags predicting them and had lower active information storage. Lastly, in the affective dynamics study (Chapter 10), both the variability of self-criticism and negativity and the inertia of negativity significantly predicted depression alongside trait rumination and person-level means of content features of rumination. However, the direction of the prediction of depression was different. It was positive for negativity inertia and self-criticism variability and negative for negativity variability. Overall, the content features of rumination exhibited trait-like properties, whereas the process features did not.

Yet, this difference was not the only set of results differentiating content features from process features. Clear differences emerged between features across all our studies, seemingly forming two clusters of features echoing the semantic distinction we had made throughout this thesis (Chapters 8, 9, 10, and 12). One cluster corresponds to what we have named so far 'content' features: negativity and self-criticism, referring to negative and self-critical thoughts. The second cluster corresponds to 'process' features: perseveration, brooding, and replaying, referring to time spent thinking about emotional experience, thinking about the causes and consequences of emotional experiences, and mentally replaying parts of emotional experiences.

Although we did not conduct cluster analyses, the patterns of results were consistent across studies. First, negativity and self-criticism were interconnected and showed similar patterns in the results: (a) they were interconnected in the between-subject network of the temporal network analysis (Chapter 8); (b) they predicted process features in the transfer entropy analyses (i.e., perseveration and replaying, respectively; Chapter 9); (c) they predicted each other in the transfer entropy analyses and had similar properties of active information storage in (Chapter 9); (d) they showed multicollinearity in predicting depression and anxiety symptoms (Chapter 10); (e) and both had a majority of explained variance by random effects in the tDCS paper (Chapter 12). In contrast, perseveration, replaying, and brooding (a) were interconnected in the mlVAR paper at the contemporaneous and between-subjects levels (Chapter 8); (b) they also were interconnected in the entropy paper and had similar high active information storage (Chapter 9); (c) replaying and perseveration both predicted executive control in the transfer entropy analyses (Chapter 9); (d) the process features showed multicollinearity in Chapter 10 when predicting depression and anxiety symptoms; (e) and they behaved similarly in the tDCS paper with similar variables predicting them, with a majority of variance explained by fixed effects (Chapter 12).

Lastly, another point of convergence was that process features never predicted content features like negativity or self-criticism. In contrast to negativity and self-criticism standing out as key driving features of rumination, process-related features emerged as consequences of the content features of rumination in our results. This is the case in the mlVAR results. And it is also the case in the transfer entropy results. Conversely, all three process-related features predicted each other and had the highest omnibus transfer entropy values, indicating they were most informed by the other variables in the network. Hence, our results suggest that the content features predict the process features of rumination but not vice versa.

13.1.2 Integration with previous findings and theoretical implications

In Chapter 1 of this thesis, we reviewed a broad range of theoretical models of rumination. How do our results relate to prior theoretical models? For starters, the influential role of the negativity feature of rumination across our studies is striking. Given that it measures how negative our thoughts are, its influential role could be best explained by relating it to goal discrepancies. The goal-progress theory posits that rumination arises and persists as a response to perceived unsatisfactory progress towards a goal or a discrepancy between reality and a goal (Martin & Tesser, 1989, 1996b). How negative one's thoughts are could be the manifestation of goal discrepancies or a lack of progress towards a goal. Given that this goal-progress mechanism is considered one of the two proximal causal mechanisms of rumination (Watkins & Roberts, 2020), this would explain why negativity predicts the other features of rumination. People would repeatedly think about these goal discrepancies, being self-critical towards themselves, replaying mentally certain parts, and wondering what the causes and consequences are of what they experienced or are experiencing. Moreover, the combined average of negativity and self-criticism (in Chapter 10) predicting depression and anxiety could mean that this composite variable captures on average how much participants thought about goal discrepancies. Importantly, we cannot exclude that some participants might experience goal discrepancies but do not think about them because instead, they distract themselves, which can be adaptive to some extent (e.g., Nolen-Hoeksema & Morrow, 1993; Watkins et al., 2000). Hence, this means negativity potentially captured the extent to which people actively thought about goal discrepancies.

From this viewpoint, if negativity captures a proximal cause of rumination (i.e., goal discrepancies), the inertia of negativity—how it persists from one time point to the next—emerges because what is causing the negative thought is unresolved: negative thoughts (and their related goal discrepancies) persist because ruminating is ineffective at addressing the cause of the goal discrepancies or reducing the discrepancies. This leads to (a) repetitive thoughts and (b) persistent negative thoughts, that is, negativity inertia.

Collectively, our results strongly suggest that negativity serves as a proxy for goal discrepancies. This finding aligns with the conceptualization proposed by the Goal-Progress theory (Martin & Tesser, 1989, 1996b) and embraced in both the Habit-Goal framework (Watkins & Nolen-Hoeksema, 2014) and the HEXAGON model (Watkins & Roberts, 2020), underscoring its fundamental role as a driving force of rumination. However, this influential role of negativity is at odds with the results from Bernstein et al. (2017, 2020) who found that, instead, self-criticism was the most influential feature of rumination. How can we best reconcile these findings? The answer lies probably in the temporal fluctuations of rumination features. Only by looking at the temporal fluctuations of rumination can one find that negativity drives rumination, as across daily life, goal discrepancies vary, and come and go, the other features of rumination following suit. By looking at the features of rumination at a single time point, Bernstein et al. (2017, 2020) were unable to observe these variations, and it is therefore likely that this is why their cross-sectional network analyses captured the influential role of self-criticism instead.

Indeed, self-criticism also plays an important role, but probably a different one than negativity. Given how closely related self-criticism and negativity were in our studies, it makes sense that self-criticism is also related to goal discrepancies. Yet, self-criticism might not reflect goal discrepancies in the same way as negativity does. Instead, self-criticism could be so closely related to negativity because it increases the likelihood of noticing goal discrepancies or interpreting events as a reflection of one's inability to live up to internal or external standards

(Martin & Tesser, 2006; Matthews & Wells, 2004). People who are self-critical towards themselves often have either high standards for themselves or interpret any deviation from their standards as extremely negative. Indeed, high self-criticism is correlated with greater ruminative tendencies and greater maladaptive perfectionism (Thew et al., 2017). Therefore, self-criticism can exacerbate the extent of the perceived goal discrepancy, contributing to more negative thoughts, whereas negative thoughts can be about self-referential events, which can trigger people to engage in self-critical thoughts. In line with this, Martin and Tesser (1996) had already theorized some of these aspects, postulating that high standards for oneself or bigger goals can lead to bigger perceived discrepancies and therefore be a risk factor for rumination. Lastly, given that self-criticism can be best viewed as a meta-cognitive process strongly associated with negative metacognitive beliefs (Kolubinski et al., 2019), our findings on the role of self-criticism are in line with the S-REF model (Matthews & Wells, 2004). Indeed, this model postulates that self-knowledge elements such as metacognitions contribute to the choice of certain regulation strategies, such as rumination, and can also make the implementation of these strategies more maladaptive. In other words, self-criticism both increases the likelihood of starting the ruminative process and contributes to making this ruminative process maladaptive.

Importantly, the negativity and self-criticism features may not just be related to the goal-progress mechanism of rumination. Indeed, the mixed model analyses in Chapter 12 (i.e., variance explained by random effects) and the active information storage analyses in Chapter 9 uncovered a trait-like aspect to negativity and self-criticism. Moreover, the composite variable of person-level means of negativity and self-criticism corresponds to the participants' tendency to experience negative and self-critical thoughts, and it predicted depression and anxiety. The most striking aspect of these results is that this dispositional nature was uncovered in two completely different settings: in a laboratory setting and in daily life, thereby strengthening the case that these two items might have captured some stable tendencies.

These stable tendencies or trait-like aspects of negativity and self-criticism can be linked to three different but complementary explanations. First, these observations are in line with prior research that showed that negative affectivity (Watson & Clark, 1984) and self-criticism (Schanche, 2013; Zuroff et al., 2016) can be considered persistent traits or personality aspects. Second, this trait-like aspect could also correspond to the second proximal causal mechanism of rumination, namely its habitual and trait-like nature, as postulated in the Response Styles Theory (Nolen-Hoeksema, 1991) and further developed in the Habit-Goal framework (Watkins & Nolen-Hoeksema, 2014). Hence, when people are in a negative mood, their choice to think about their negative mood and to be self-critical is a general tendency, a habit, that has been influenced, for instance, by their upbringing and the strategies they learned to use as a kid or teenager (Manfredi et al., 2016). Third, this trait-like aspect can also be an indirect manifestation of a negative interpretation bias. Because we did not measure negativity bias, this inference is extremely speculative. However, it would be in line with the HEXAGON model, which postulates that a negative interpretation bias can exacerbate rumination through the two proximal causal mechanisms (Watkins & Roberts, 2020). Negative interpretation bias is not going to cause rumination. Instead, it will increase the likelihood that a person will see situations in a bad light, highlighting discrepancies. In other words, someone with a negative bias will negatively interpret any situation and therefore be more likely to have negative thoughts and have reasons to be self-critical. Rather than any single explanation being the right one, it is likely that a combination of these processes explains the trait-like aspects in the results of Chapters 9 and 12. In sum, this means that (a) both proximal causes postulated in the Habit-Goal framework and the HEXAGON model of rumination might have been captured by the items of negativity and self-criticism, and (b) that the habitual nature of rumination and the frequency of rumination in daily life could reflect a habitual process, a stable or personality-dependent process, or a negative interpretation bias, with all these processes possibly contributing to each other.

Given that negativity and self-criticism seem most related to the two proximal causal mechanisms of rumination, to what do the process features of rumination relate? Based on our results, the process features do not reflect the causal mechanisms of rumination but instead their consequences. Perseveration, brooding, and replaying do not refer to a specific valence of thoughts, neither positive nor negative, and instead better correspond to the output of the ruminative process and how long it lasts. Indeed, negative thoughts or self-critical thoughts, however intense, can be very short, whereas high scores on perseveration, brooding, and replaying de facto imply that some time has been spent thinking and that the thought process has been unproductive to some extent (Watkins, 2008).

That being the case, the repetitiveness of ruminative thoughts (i.e., high perseveration, higher replaying, higher brooding) could be viewed as an emergent property of a failed regulation process. Rumination is repetitive because rumination is ineffective at addressing the causes—goal discrepancies and a habitual response to negative affect—, partially because these discrepancies are often in the past and are immutable. Hence, these results support the idea that rumination is often maladaptive because it is ineffective first and foremost; because it is ineffective (i.e., first-order effect: it does not resolve the trigger), it becomes repetitive, lasts over time, and this repetition induces second-order consequences such as sustained physiological stress (Brosschot et al., 2006), development of negative interpretation biases (Watkins & Roberts, 2020), impaired problem-solving, and loss of social support (Nolen-Hoeksema & Davis, 1999).

These results, emphasizing the importance of negativity and self-criticism rather than the process features of rumination, are in stark contrast with the 'Repetitive negative thinking' (RNT) framework. This RNT framework emphasizes that the process-like features of RNT (e.g., uncontrollability) rather than the content (e.g., valence) are key and that different forms of RNT are characterized by similar processes but disorder-specific content (Ehring & Watkins, 2008). Here language generates a problem because 'processes' could refer to causal or mechanistic processes like goal mechanisms and habits. However, Ehring and Watkins focus on features such as repetitiveness and controllability when talking about 'process' features, which, in my interpretation, are process-like features, but in a descriptive sense—outcomes resulting from underlying causal processes. As Carver also put it, "recurrence of the thoughts is necessary only when your efforts aren't moving you forward. Surely at the descriptive level a distinction between recurrence and nonrecurrence of the thoughts is useful. But emphasis on this distinction tends to obscure the fact that both kinds of thought have the same underlying purpose, moving the person towards the goal" (Carver, 1996, p. 51).

Similarly, the assertion by Ehring and Watkins that forms of RNT are characterized by different and disorder-specific content can be reinterpreted. Describing the content with features such as intrusiveness and temporal orientation, apart from the valence, suggests that these features can indeed be specific to different forms of RNT. For example, thoughts regarding compulsions can feel more intrusive than ruminative thought; the content of rumination will more likely have a past or present orientation, whereas worrying will have a future orientation. However, all these types of thoughts will have a negative valence. I would go even further by saying that all these thoughts are negative because they reflect goal discrepancies. For instance, worrying about taking the plane consists of worrying about a future situation in which there is a discrepancy between one possible and realistic scenario (for the person that worries)—dying in a plane crash—and their ideal situation—staying alive. Another example could be a student who is anxious about an exam and worries about it. There is again a discrepancy between their goal—succeeding the exam—and a likely scenario—failing the exam. If the student did not care about succeeding, if it was not their goal, they would have no reason to worry. Thereby, I propose that a better term for repetitive negative thinking could be 'goal-directed cognition'. This term refers to a mechanistic process underlying the thoughts, not the resultant of it (e.g., recurring). I will elaborate further on this idea in Chapter 14, when outlining a blueprint for a new theory of rumination.

A limitation of this integration of our results with prior research is the assumption that negativity is a proxy for goal discrepancies. Although this perspective is in line with prior research, we have not tested this assumption directly. Instead of inferring that negativity reflects goal discrepancies, researchers could therefore thrive to measure goal discrepancies in future research. They could do so directly, either qualitatively, by asking participants to describe the topic of their thoughts whenever they ruminate, or indirectly, by asking participants whether their thoughts are about goal discrepancies, with items measuring various features of these goal discrepancies (e.g., the extent of the goal discrepancy, the perceived controllability, etc.). In addition to measuring negativity and the other features of rumination, researchers could also measure goal discrepancies indirectly by measuring affect or emotions, as has been done in the past (e.g., Moberly & Watkins, 2008).

Other features of rumination could be considered in future research to further expand on the links made in this section. Even though we relied on features highlighted in Nolen-Hoeksema's prominent view of rumination (Nolen-Hoeksema, 1991; Nolen-Hoeksema et al., 2008), other features could be important or complete the network conceptualization of rumination. For instance, the perceived controllability of the situation, the perceived controllability of thoughts, or the temporal orientation of thoughts (i.e., whether they refer to the past, the present, or both). In doing so, future research could help delineate driving features of rumination from features that are a byproduct of the ruminative process.

A last implication about rumination specifically is regarding the perseverative cognition hypothesis (Brosschot et al., 2006). Indeed, our results open up new paths to test this hypothesis. Even though we did not measure physiological arousal or heart rate variability, the inertia of negativity or the perseveration feature of rumination could be associated with concurrent maintenance of physiological arousal and stress. Both correspond to a different aspect of the length of ruminating. Negativity inertia corresponds to the extent to which having negative thoughts at one time point is associated with negative thoughts at the next time point, thereby implying that people had negative thoughts between the two measurements. Perseveration corresponds to the time one has spent thinking about an emotional experience during a single timeframe (four hours in our ESM study). Future research could therefore investigate whether either is associated with concurrent physiological stress and its downstream consequences, thereby testing this hypothesis in daily life. Moreover, beyond reflecting failed emotion regulation and more goal discrepancies, negativity inertia might be a predictor of depression (Chapter 10) because its sustained emotional activation is accompanied by sustained physiological stress that therefore could cause long-term physiological consequences. The physiological consequences play a crucial role in depression, which has been considered a physiological syndrome in addition to a psychological syndrome (Hasler, 2010).

13.2 Rumination and its associations with executive control

13.2.1 Comparison of our findings

Reconceptualizing rumination as a multifaceted construct led to an interesting set of findings regarding the associations between rumination and executive control. Indeed, rumination features predicted worse executive control across two different methods of analysis (Chapters 8 and 9). Moreover, although there was a concurrent association between negativity and executive control at the contemporaneous level of the mlVAR analysis, it was not directed; in sum, executive control never predicted any of the rumination features.

The exact pathway linking rumination and executive control, however, differed between the mlVAR and the transfer entropy analyses. In the mlVAR analysis, only negativity predicted worse executive control at the next time point and was associated with executive control within the same time point. In contrast, in the transfer entropy analysis, a different pathway emerged: negativity and self-criticism predicted perseveration and replaying, respectively, which in turn predicted executive control within the same timeframe. Additionally, a slight divergence was observed in the timescale of the associations: the mlVAR analysis found lagged predictions over time (i.e., negativity predicting worse executive control at the next time point) and within the same time point, while mTE showed *only* contemporaneous associations.

Finally, in our tDCS study, tDCS had no impact on state rumination, even when looking at it through the lens of a moderated mediation or through the lens of rumination as a multifaceted construct. This null finding is in line with the results from our systematic review, which highlighted that almost half of tDCS studies failed to find an effect on rumination.

13.2.2 Integration with previous findings and theoretical implications

In this thesis, our goal was first to reconceptualize rumination as a dynamic, multifaceted construct and then to examine the association between rumination and executive control through this new lens. We focused on two hypotheses regarding the associations between rumination and executive control: the impaired disengagement hypothesis (Joormann, 2010; Koster et al., 2011) and the resource depletion account (e.g., Philippot & Brutoux, 2008). In doing so, we did not seek to settle the debate once and for all but instead to provide some new evidence and open paths for future research.

The results from both Chapters 8 and 9 support the resource depletion account, with rumination predicting worse executive control. Importantly, these two studies suggest different pathways by which rumination affects executive control. In the mlVAR analyses in Chapter 8, only negativity was directly associated with worse executive control within the same time frame (i.e., a four-hour period) and predicted executive control at the next time point (i.e., during the next four hours). In contrast, in Chapter 9, negativity predicted perseveration, self-criticism predicted replaying, and both perseveration and replaying predicted executive control within the same time point. Admittedly, in contrast to the association between content and executive control uncovered in Chapter 8, the results in Chapter 9 are more directly in line with the resource depletion account, given that executive control is directly linked with the two features of rumination that most reflect the potential time spent ruminating. Therefore, the transfer entropy analyses were perhaps better able to handle the complex interplay of all the rumination features and were therefore better at revealing the pathway linking the causal factors of rumination (negativity/goal discrepancies) with its consequences (i.e., recurrence) and their impact on concurrent executive control.

All in all, our results support the resource depletion account; these findings based on intensive longitudinal data from daily life corroborate what had previously only been found in an experimental setting (see Table 3, p. 55). Therefore, these results are the first to provide support for the resource depletion account based on intensive longitudinal data in daily life. Yet they do not converge on the exact same pathway or on the timescale by which rumination negatively affects executive control. Hence, future research should seek to replicate and extend these findings.

A limitation to this theoretical interpretation of our findings, however, is that we only investigated executive control (referred to as 'attention control' in those chapters) with one self-report item: it measured participants' ability to voluntarily direct their attention and concentrate on a task. Moreover, we did not validate this item in the same way we validated the ESM items for rumination. Given that it was used to measure executive control in daily life, it is probably a more ecologically valid measure compared to computerized tasks in a laboratory setting. Yet, it might not have the same construct validity in the same way that self-reported trait measures of executive control do not strongly correlate with computerized tasks, with variations depending on the different executive functions (Snyder et al., 2020). Some meta-analyses even suggest that there are no associations between trait measures and task performance (Clarke & Todd, 2021; Todd et al., 2022). Lastly, some authors suggest that questionnaires and tasks might measure different but complementary aspects of executive control (Friedman & Gustavson, 2022). Importantly, however, none of these studies considered self-report momentary measures of executive control in daily life. Thus, we cannot know how much our item captured participants' executive control abilities in the moment or which aspect of executive control it captured. Future research should therefore either seek to validate a self-reported momentary measure of executive control or investigate whether it shows similar or better associations with task performance compared to trait questionnaires. Alternatively, researchers could use short computerized tasks on smartphones to test specific executive functions in daily life (e.g., Wilks et al., 2021; Zhaoyang et al., 2021).

In stark contrast with the evidence for the resource depletion account, we found little evidence for the impaired disengagement hypothesis across our studies. As has been previously noted, in the results from Chapters 8 and 9, there were no directed associations from executive control to rumination. The only evidence in favor of the impaired disengagement hypothesis was at the contemporaneous and between-subject levels in the mlVAR analysis, as shown in Table 22. But even so, given that these associations are undirected, they only provide weak evidence for the causal hypothesis of the impaired disengagement hypothesis. Moreover, the findings of Chapters 11 and 12 provided mixed evidence for it. We reviewed several studies that used tDCS to stimulate the dlPFC, serving as a proxy for improving or interfering with executive control, to investigate its impact on rumination. The results of the systematic review were inconclusive, highlighting that stimulating the dlPFC could indeed influence rumination, providing some support for the impaired disengagement hypothesis. However, the studies were heterogeneous, and the results were inconsistent. Moreover, the tDCS study we conducted resulted in null findings. We did not find any support for a mediation effect of executive control or a moderation by trait rumination of the effect of tDCS on state rumination. This hypothesis of moderated mediation—i.e., tDCS impacts state rumination via improved executive control (the mediating variable) only among those exhibiting a general tendency to ruminate (the moderating variable)—remains therefore only directly supported by one study that we had included in our systematic review (Vanderhasselt et al., 2013). All in all, our results and past results do not offer strong support for the impaired disengagement hypothesis or the ability of tDCS to modulate rumination.

An important limitation of some studies included in our systematic review and our tDCS study is the use of a community sample. As discussed in Chapters 11 and 12, tDCS might be ineffective at improving executive control because of a ceiling effect in healthy volunteers (Coussement et al., 2020) or might even cause detrimental effects by interfering with optimal neural homeostasis (Habich et al., 2020). To best address this limitation, future studies should measure executive control abilities at baseline (i.e., to test the ceiling effect and account for baseline executive control abilities in the effect of tDCS), recruit clinical participants, or do both. In this way, future research will be directly able to test the assumptions of the impaired disengagement hypothesis by verifying that any effect of tDCS on rumination is accompanied by a clear effect of tDCS on executive control in the expected direction.

Additionally, given that we measured state rumination as a multifaceted construct, we thought we might observe that tDCS does not influence all features of rumination in the same way. Our results did not support this hypothesis, as we found no effect of tDCS on any of the features. However, in post-hoc analyses, a pattern did emerge in the association between N-back performance/stress and rumination features. The N-back RT and stress during the resting period were found to predict perseveration, brooding, and replaying to some extent, indicating a relationship between task performance/stress and these specific rumination features. However, these factors did not predict negativity or self-criticism. Furthermore, our analysis suggests that these fixed factors—the N-back RT and stress—are the primary contributors to variations in perseveration, brooding, and replaying, as opposed to the within-subject variability, represented by the random effects[2]. This result suggests that people might have ruminated about their performance on the N-back task in addition to the stress-inducing backward counting task, but that neither their N-back performance nor their stress explained the extent to which their thoughts are negative and self-critical. These latter features of rumination may be more reflective of stable, trait-like dispositions, as discussed previously. This difference between process features of rumination and content features of rumination might be important to keep in mind to better specify the associations between rumination and executive control: deficits in executive control might make thoughts more repetitive, but executive control will not directly influence the negativity or self-critical aspect of thoughts.

Only one other study investigated the associations between executive control and the same features of rumination. Bernstein et al. (2017) found slightly different results between the N-back and the same five features of rumination. Performance on the N-back (proportion of correct responses) was only significantly negatively correlated with brooding. Because they relied on partial correlations and the proportion of correct responses on the N-back, our results are not directly comparable. Future research could therefore further explore the associations between the process features of rumination (perseveration, replaying, and brooding) and executive control tasks.

Because the main focus of this thesis was not on the associations between rumination features and executive control, we sought to interpret our results considering two contrasting hypotheses and open up new paths for future research in doing so. Consequently, we did not investigate alternative hypotheses, such as a potential bidirectional relationship between rumination and executive control. Although our temporal studies could technically have uncovered such an association and did not find one, our experimental study only investigated whether increasing executive control through tDCS stimulation would reduce rumination, not

[2] As a reminder, these findings are based on the difference between the marginal R-squared values and the conditional R-squared values. Marginal R-squared values represent the proportion of variance explained by the fixed factors alone, while conditional R-squared values represent the total variance explained by the model, including both fixed and random effects. In our analysis, the similarity of the marginal and conditional R-squared values for perseveration, brooding, and replaying suggests that the fixed factors account for most of the explained variance, with minimal contribution from within-subject variability.

the opposite. Researchers could therefore find ways to best investigate this bidirectional association in future studies.

Chapter 14.

Theoretical implications

As I delve into the theoretical implications of our empirical findings, two central themes emerge that prompt a reevaluation of existing paradigms. The first theme challenges the traditional view of the role of executive control in the context of rumination. Grounded in the empirical evidence we uncovered, I critically examine the interplay between rumination and executive functions, challenging the core assumptions of the resource depletion account and the impaired disengagement hypothesis. Leveraging recent research into mental fatigue and cognitive resource theories, alongside insights from the Self-Regulatory Executive Function (S-REF) model, I propose a nuanced reassessment of how rumination may both be influenced by and influence executive control. This analysis will not only interrogate the role of impaired executive control in fostering rumination but will also consider how robust executive control might paradoxically underpin the persistence of rumination, offering a novel perspective on the function of the dorsolateral prefrontal cortex (dlPFC) and the potential effects of transcranial Direct Current Stimulation (tDCS).

Moving beyond critique, the second theme involves constructing a new theory of rumination and repetitive negative thinking. This theoretical development is necessitated by the clear evidence from our findings supporting the multifaceted and dynamic nature of rumination. The ensuing sections will integrate these innovative viewpoints with established theoretical constructs, forging a blueprint for a comprehensive theory that encapsulates the temporal dynamics of rumination and similar repetitive thoughts, the intricate roles of executive control, and the broader ramifications of this cognitive process.

14.1 Reconsidering the role of executive control in rumination

14.1.1 Reexamining the resource depletion account

According to the resource depletion account, rumination, through the monopolization of cognitive resources, interferes with concurrent executive processing and effective resource allocation, which translates to impaired performance on a wide range of tasks (Brinker, 2013; Philippot & Brutoux, 2008; Watkins & Brown, 2002). However, the mechanism underlying this effect has not been investigated in great detail. For instance, our results indicate that rumination either impairs executive control prospectively—worse negativity at one point leading to worse executive control at the next time point—or only impairs it within the same time point. This raises the question as to whether the 'resource depletion' effect only occurs concurrently with rumination or also persists after a ruminative episode. Moreover, this further questions the hypothesis that rumination occupies cognitive resources, which supposes that there are resources in the first place. If these resources can be occupied, can they also be depleted, as the name of the 'resource *depletion* account' suggests? This could explain the lasting effects of rumination on executive control.

More specifically, two separate mechanisms could lead to the same observation of impaired executive control: the exhaustion of a finite pool of cognitive resources or interference with the optimal allocation of available resources. The problem with the first supposed mechanism (and the name of the 'resource depletion account'[1]) is that this view of having a limited set of cognitive resources that can be depleted has been criticized and is not supported by recent findings (Forestier et al., 2022). However, research shows that the feeling of mental fatigue, thought to reflect depleted cognitive resources, has no relation to the performance of a task, with some research showing people could work for hours on end during days without their performance suffering (Huxtable et al., 1945). Assuming your basic needs are met, and one is well rested, it seems that there is no mental effort that one cannot do. As Badre (2020, p. 204) puts it, "[…] a reasonable heuristic would be if the motivation is there, so is the mental capacity. But the motivation is not something to take for granted." Therefore, another explanation is required.

The mental fatigue and worse performance would not come from a depletion of mental resources. Instead, the aversive experience of mental fatigue has been theorized to emerge from the opportunity cost of doing one task while not being able to do other tasks (Kurzban et al., 2013). For example, it might feel more tiring to do chores and file taxes while being under pressure to write a discussion section of a thesis and at the same time handle administrative duties related to unemployment, compared to doing chores and filing taxes on a Sunday afternoon after a productive week that left the to-do list empty. I certainly also experienced the role opportunity cost or alternatives when writing this discussion[2]. Therefore, the effect of rumination on performance on tasks over time, or rumination being tiring, might be best

[1] We decided to use the term 'resource depletion account' because it was objectively more commonly used than the term 'resource allocation hypothesis'. However, the nuance in meaning not being discussed in the literature on rumination, we did not discuss it either, which is something we overlooked.

[2] In the final two weeks before the submission of my thesis, with the deadline approaching and being highly motivated, with all my friends and family aware that all of my attention was going to the thesis (i.e., making it easier to say no to alternatives like going out, resulting in less alternatives/external demands), with my parents taking care of my dog, with a schedule of blocking social media and entertainment (i.e., reducing the possibilities of self-distractions), with my phone in silent mode for most of the day, and with a clear conviction that finishing my thesis was my priority number 1, by sleeping 8-9h a day, by eating enough, by taking regular breaks or doing short exercise bouts, I felt no cognitive fatigue, even after writing and thinking intensively for sometimes more than 8-10h a day (of real, timed!, 'deep work'). On the contrary, sometimes after a great day, I would feel ecstatic! The only time I felt bad—which I could have interpreted as 'mental fatigue' and not just normal physical fatigue—was when I regretted not being able to do other activities, or when I regretted having taken too long of a break and feeling the resistance to start work again.

explained by the motivational opportunity cost induced by ruminating while being aware of neglecting other tasks.

The second explanation of the 'resource depletion' effect is that rumination does not deplete cognitive resources but instead allocates the available resources inefficiently. Efficiency in this context could either refer to the subjective efficiency of how one would like to spend their attention or to the more rational view of efficiency as whether the use of their attention is adaptive or has maladaptive consequences. The latter option is in line with the predictions of the S-REF model.

The Self-Regulatory Executive Function (S-REF; Matthews & Wells, 2004) comprises three levels: a lower level of processing networks, a supervisory executive system, and a self-knowledge level. The lower levels support the automatic processing of various types of information (e.g., incoming stimuli, representations of somatic states, etc.). The supervisory executive system is activated by motivationally significant external stimuli and intrusive thoughts. It appraises these stimuli and computes any relevant discrepancy. If a discrepancy is found, the system searches for adapted coping options, selects and initiates a coping strategy, and monitors its implementation. Hence, because rumination is related to goal discrepancies, and self-relevant information, a person might be automatically motivated to engage in rumination over fully engaging in a task. For instance, after a bad argument with a significant other or a good friend, one might feel unable to concentrate on a task at hand and find themselves ruminating about what just happened. Hence, ruminative thoughts may interfere with efficiently directing attention to a concurrent task and performing it to our best ability if it requires executive control skills.

This allows us to better interpret our findings. The results from the transfer entropy analyses (Chapter 9) might have better captured this process than the mlVAR analyses (Chapter 8). In line with the explanations in this section, the transfer entropy analyses showed that *negativity and self-criticism*—reflecting goal discrepancies, that is, motivationally relevant thought content—*predicted perseveration and replaying*—reflecting a significant allocation of attention and time towards this motivationally relevant thought content—which in turn *predicted worse executive control* within the same time point.

In summary, while traditional views have conceptualized rumination as a cognitive process that depletes executive resources, leading to impaired task performance, our reinterpretation of our findings and the resource depletion account suggest a more complex picture. Rumination, as underscored by the S-REF model (Matthews & Wells, 2004) and the Goal-Progress Theory (Martin & Tesser, 1996b), appears to be a highly goal-directed process, intricately linked with executive control functions. Rather than depleting cognitive resources, rumination may involve the strategic allocation of these resources towards internally motivated goals[3]—the bigger the goal discrepancy, the more motivated they might be to solve it and therefore ruminate more (Martin & Tesser, 1989; Roberts et al., 2013). This reconceptualization opens up new avenues

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[3] Additionally, while this perspective assumes rumination initiation is under volitional control, rumination may sometimes arise from unintentionally triggered thoughts. For example, a person could have an intrusive thought about a bad memory, which then activates perceived goal discrepancies, motivating rumination.

for understanding why individuals engage in rumination and how it may impact their cognitive functioning over time. The challenge now lies in extending this understanding into practical applications and interventions that can effectively address the maladaptive patterns of rumination without inadvertently reinforcing them.

14.1.2 Impaired Disengagement Hypothesis: A New Perspective from S-REF

The motivational underpinnings of rumination also challenge the impaired disengagement hypothesis. Rumination may not only or always be a byproduct of an inability to divert attention but may be an intentional engagement driven by the need to resolve perceived goal discrepancies. This aligns with the perspective that individuals may be intrinsically motivated to ruminate, fueled by a desire to reconcile these discrepancies, with the executive system playing a facilitative role. This alternative explanation to the impaired disengagement hypothesis might help explain the mixed findings in neuromodulation research, as highlighted by our systematic review and by our null results in Chapter 12.

In other words, any observed difficulty disengaging from negative thoughts may therefore not be due to impaired executive control. Instead, a person may have trouble disengaging from these negative thoughts because they are intrinsically motivated to ruminate to address the goal discrepancy. Even though ruminating might have negative consequences for them, it is a motivational process that still urges them to ruminate, much in the same way a drug addict feels compelled to take another dose of drugs to relieve a craving. However, someone who ruminates does not crave drugs; they crave a happy life without goal discrepancies.

From this perspective derives another important point: people will only stop ruminating if they are more motivated to engage in another task or if something else takes up their attention and breaks their chain of thoughts (i.e., deactivates the representation of a goal discrepancy). Thereby, a person may voluntarily stop to ruminate because (a) they know that it does not address goal discrepancies, (b) they want to avoid its negative consequences, and (c) they know which alternative coping strategies they can implement instead (i.e., new metacognitive beliefs and knowledge after, for example, psychoeducation in therapy).

In summary, the very same behavior—ruminating—could be explained by two processes: (1) people with poor executive control may ruminate more because they are unable to suppress thoughts or direct their attention to other matters (i.e., the impaired disengagement hypothesis; Koster et al., 2011), and (2) people with normal executive control may ruminate more if they are intrinsically driven to ruminate and may have no other way to cope with the goal discrepancy that triggered rumination (Levinson et al., 2012; McVay & Kane, 2010). This perspective has, to my knowledge, not yet been emphasized in studies about the effects of tDCS on rumination but has been discussed in the context of mind-wandering (McVay & Kane, 2010).

How is this view supported by research, and how does it specifically relate to the findings of this thesis? This perspective could help explain our null findings in Chapter 12 and in our systematic review. Indeed, first of all, the left dlPFC is involved in supporting goal-directed behavior (Genovesio et al., 2005) and manipulating information in working memory (Barbey, Koenigs, et al., 2013). Second, dopamine, which plays a crucial role in supporting goal-directed behavior in the prefrontal cortex (Cools, 2008; Ott & Nieder, 2019), has been shown to help stabilize the representation of a task or goals in working memory, whereas low-value information or tasks and low dopamine can make it easier to lose that information from working memory (Brozoski et al., 1979; Cools, 2008; Watanabe et al., 1997). This implies that when a person is engaged in and motivated to ruminate, the representation of a goal is stabilized in their working memory. Altogether, this gives a rationale as to why executive control supports rumination and why upregulation of the left dlPFC via anodal tDCS could be ineffective at reducing rumination or might even increase it. In other words, if participants are engaged in ruminative thoughts while on a task and undergoing tDCS, or ruminate even after a stimulation (i.e., tDCS effect can last for several hours after the end of the stimulation; Monte-Silva et al., 2013b; Nitsche et al., 2003; Nitsche & Paulus, 2001b), the effects of tDCS might reinforce this thinking pattern.

Moreover, the role of the left dlPFC in prioritizing cognition in a context-dependent manner (Badre & Nee, 2018) adds complexity to the debate around the role of executive control in rumination. The dlPFC is active when task demands are high, but it is also active when prioritizing personally relevant off-task thoughts when environmental demands are low (Turnbull et al., 2019). Therefore, as Turnbull et al. (2019) note, both possible explanations for the observation that people have difficulties disengaging from their thoughts might be complementary and enabled by the dlPFC: "[The] dlPFC may contribute to the decoupling of attention from external input that is thought to be necessary for efficient processing of self-generated information" (Turnbull et al., 2019, p. 6).

Therefore, this interpretation of our null results challenges the notion that rumination is merely a byproduct of impaired executive control. Instead, it highlights the need for a more intricate understanding of the motivational drives underlying rumination and how they interact with executive control. This has significant implications for both the conceptualization of rumination and the development of targeted interventions.

An important limitation of the present work is that it relied on a community sample mainly composed of young adult students. Future research should aim to replicate these findings in clinical populations diagnosed with emotional disorders like depression or anxiety who exhibit higher trait rumination or impaired executive control. Additionally, assessing executive control abilities at baseline, before the tDCS sessions, would allow for testing whether tDCS effects on state rumination are moderated by initial executive control capacity. TDCS may only benefit those with poorer baseline executive control, whereas it could have detrimental effects on those with already high executive control. Indeed, tDCS may interfere with efficient processing in healthy subjects (for a recent review, see de Boer et al., 2021; Vanderhasselt et al., 2023). Although several studies have reported adverse effects of tDCS in healthy participants, the mechanisms underlying these effects are still unclear. One possible explanation highlighted by Habich et al. (2020) is that healthy participants function at a neuronal homeostatic optimum and that "tDCS-induced alterations beyond the endogenous range of activity of the system will be actively counteracted in an effort of the brain to preserve an activity level within the optimal range (O'Leary and Wyllie, 2011), which is not necessarily equivalent to a high level of activity (Schröder and Degen, 2020)" (p. 3).

Another limitation is that we only measured one specific facet of executive control, working memory updating, using the N-back task. Our single ESM item on perceived executive control relates to general abilities to voluntarily direct attention. Further work should incorporate multiple tasks tapping distinct executive functions, in conjunction with multifaceted state rumination measures, to delineate the links with specific executive control processes. Overall, enhancing the understanding of the nature of rumination-executive control associations would involve extending this research to clinical groups and diversifying measures of executive functions.

14.2 Towards a blueprint for a new theory of rumination

In the preceding chapters, we have navigated through a landscape of intricate relationships between the features of rumination and their interplay with executive control. Our empirical findings challenge the static perspective traditionally held in rumination research and suggest that a dynamic, multifaceted conceptualization is not merely appropriate but essential. The limitations and gaps revealed through our integration with the extant literature underscore the need for a theoretical recalibration.

Existing models, while foundational to our current understanding, exhibit constraints that our findings bring to light. They often encapsulate rumination within too narrow a scope, omit key mechanisms or features like goal discrepancies or self-critical tendencies, or rest on assumptions that no longer align with the latest empirical evidence. For instance, our results prompted us to seek an alternative explanation for the resource depletion account, and the 'Repetitive Negative Thinking' framework may overemphasize certain elements at the expense of others. Additionally, the HEXAGON model, despite its contributions, does not encapsulate the full spectrum of processes related to rumination.

To forge a path forward, we must construct a theory that embraces the multifaceted and dynamic nature of rumination as elucidated by our research. This theory must integrate not just the cognitive aspects of rumination but also its affective, physiological, and temporal dimensions. It must account for how rumination interacts with executive control, not as a depletive force but as a strategic allocation of cognitive resources, influenced by motivation and goal-directed behavior.

In this next section, I will outline the core elements of a new theory that encapsulates these insights. Drawing from our results and from prior theories such as the Goal-Progress Theory, the Self-Regulatory Executive Function (S-REF) model, and the Habit-Goal framework, along with new empirical insights, this prototheory (Borsboom et al., 2021) aims to provide a comprehensive understanding of rumination. It will consider the triggers of rumination, such as goal discrepancies and habit formation, and delineate the factors that influence the ruminative process. Through this lens, we will also explore the emergent properties of rumination—its repetitiveness and persistence—and the resultant physiological and psychological consequences. This prototheory will serve as a preliminary but robust synthesis of empirical insights and theoretical advancements, setting the stage for future research and clinical applications.

14.2.1 Key ingredients of a blueprint for a new theory based on our findings

The empirical journey of this thesis has yielded critical insights that serve as the bedrock for a new theoretical understanding of rumination. These key ingredients, derived from our findings, will form the pillars of the proposed theory:

1. **Goal discrepancies as a central mechanism**: Our findings prominently feature negativity as a driving force behind other rumination characteristics, suggesting it may reflect unresolved goal discrepancies. A new theory must, therefore, place goal discrepancies at the core, proposing that they are the primary engine that triggers and sustains the ruminative process.

2. **Metacognitive modulation of goal discrepancies**: Self-criticism, intricately linked with negativity, could amplify the awareness of goal discrepancies. This aligns with the metacognitive aspects of the S-REF model, positioning self-criticism as a pivotal moderator that heightens rumination intensity due to a heightened awareness of unmet internal standards and the belief that not meeting these standards is inherently bad.

3. **Distinction between content and process features**: The clear distinction we observed between content (negativity and self-criticism) and process (perseveration, brooding, replaying) features of rumination allows us to separate the catalysts of rumination from their resultant patterns. This differentiation is vital to our theory for understanding the triggers and outcomes of the ruminative cycle.

4. **Stable dispositions and rumination-as-a-habit**: The trait-like quality of negativity and self-criticism indicates that certain individuals may be predisposed to rumination due to enduring personality traits or habitual thought patterns, in line with the Response Styles Theory (Nolen-Hoeksema, 1991). Recognizing this propensity is crucial for the theory to account for individual variations in ruminative tendencies.

5. **Emergent property of repetitiveness**: Perseveration and replaying were predicted by negativity and also self-criticism. Given that this could indicate that thoughts are repetitive because the underlying cause is unaddressed, the repetitive nature of rumination could thus arise from failed attempts to resolve goal discrepancies, leading to a self-sustaining cycle of rumination. This notion of recurrence as an emergent property highlights the inefficacy of rumination as a regulatory strategy and will be a key concept within the theory.

6. **Strategic allocation of cognitive resources**: Our findings and our reexamination of the resource depletion account in the previous study suggest that rumination involves a strategic, albeit maladaptive, allocation of cognitive resources, driven by the

motivational salience of the unmet goals, rather than an actual depletion of cognitive capacity.

7. **Reconceptualizing the executive control-rumination relationship**: The lack of strong support for the impaired disengagement hypothesis necessitates a reevaluation of the relationship between executive control and rumination. The theory will propose that while executive control may not directly cause rumination, it is nonetheless impacted by the content and process of ruminative thought, influencing overall cognitive function.

Each of these ingredients will be integrated into the comprehensive framework of our new theory, which aims to provide an understanding of the ruminative process, its antecedents, and its consequences. The goal is to provide a preliminary synthesis of empirical insights and conceptual refinements to date into an updated theory of rumination that captures its complex and dynamic essence. This will, however, not be a fully-fledged-out theory, but instead an initial outline of all the components—a prototheory (Borsboom et al., 2021).

Given that our findings can be linked to the two core mechanisms highlighted in recent theories (Watkins & Nolen-Hoeksema, 2014; Watkins & Roberts, 2020), I will first briefly describe again the two core mechanisms (triggers) of rumination: goal discrepancies and habit-formation. Then further drawing from our results and prior research, I will touch upon a non-exhaustive list of variables that could influence the goal-related regulation process[4]. I separate these factors into (a) factors that will modify the perception of goal discrepancies (i.e., increasing or decreasing the likelihood a goal discrepancy is perceived), (b) factors that will modify the likelihood of rumination being used when a goal discrepancy is detected, (c) factors that can maintain rumination and make it more maladaptive, (d) emerging properties (i.e., the repetitiveness), (e) consequences of rumination, and (f) the underlying circuitry.

14.2.2 *Triggers of rumination*

Goal discrepancies

In developing a new, unified theory of rumination, it is essential to incorporate and reevaluate the comprehensive insights provided by Martin & Tesser on the nature of goals and their influence on cognitive processes. They have extensively explored the hierarchical structure of goals, the conflicts that can arise between them, and their impact on information processing (Martin et al., 1993; Martin & Tesser, 1989, 1996b, 1996a, 1996c, 2006). Their work serves as a foundation for understanding rumination in a broader context and understanding the influential role of negativity in our studies.

Martin & Tesser have conceptualized rumination as a form of recurrent thinking that encompasses a range of cognitive activities, such as problem-solving and worrying. They argue that these forms of thinking are functionally similar as they serve the larger purpose of goal

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[4] In many ways, there are parallels to be made and many similarities with the Extended Process Model of emotion regulation (Gross, 2015), but for sake of brevity I will not detail these.

pursuit, whether the goals are actively being worked towards or are temporarily paused. In their view, rumination is not limited to negative thought patterns but is a more general process related to goal management.

Our findings completely align with this perspective, as we discussed in Section 13.1.2. Negativity and self-criticism drove the other features of rumination, not the opposite. Therefore, instead of supporting the perspective of 'Repetitive Negative Thinking' (Ehring & Watkins, 2008), which emphasizes the repetitive nature of rumination, I instead suggest that a new theory of rumination and similar types of thoughts should align with the perspective that these types of thoughts serve a common purpose—addressing goal discrepancies (Carver, 1996).

In Section 13.1.2., I suggested shifting away from the term 'repetitive negative thinking' as it emphasizes a resultant feature rather than an underlying mechanism. Terms that refer to observable features of reality (e.g., the repetitiveness of worry and rumination) are useful to talk about these phenomena but can be misleading when constructing explanatory theories; indeed, these features, such as repetitiveness, are not part of the mechanisms that generated this phenomenon. Moreover, I also suggest a shift from using 'rumination' as a catch-all term (as initially suggested by Martin and Tesser; Martin & Tesser, 1996b, 1996a) given that this term is commonly used to refer to a specific type of thought. Instead, I propose adopting a term such as 'goal-directed cognition' (GDC) that emphasizes the underlying processes that drive various forms of repetitive thought, including rumination, worry, and obsessive thinking. This term more accurately captures the generative mechanism—namely, the orientation towards goals—that give rise to these thought patterns, rather than focusing solely on their descriptive features, such as their reoccurrence. By redefining rumination within the framework of GDC, I can create a theory that not only addresses the specific phenomenon of rumination but also encompasses a wider range of cognitive activities that share the common thread of goal-directedness, such as worry, obsessions, problem-solving, etc. This approach allows us to better categorize and understand different cognitive phenomena based on their functional equivalence in relation to goals.

The central mechanism of goal-directed cognition (GDC) is to raise awareness of goal discrepancies and initiate progress towards goals (Martin & Tesser, 1996a, 2006). People constantly evaluate the progress they make towards achieving their goals, and they change their decisions and behaviors based on this evaluation. When they fail to make progress towards a goal, when this progress is perceived as unsatisfactory, when they perceive a threat to the attainment of one's valued goals, or when they realize a valued goal cannot be achieved, they effectively perceive goal discrepancies, that is, discrepancies between their goals and the reality of the past, the present, or an imagined future. These discrepancies trigger GDC. When goal discrepancies are in the past or in the present, the GDC is referred to as 'rumination' (e.g., "Why did I act this way?" or "Why I am feeling this way now?"), whereas when the goal discrepancies refer to a threat to future goal-progress or attainment, the GDC is referred to as 'worry'. For example, if a person finds themselves ruminating at night about how miserable they feel at their job, these thoughts can quickly alternate between thoughts about the past (e.g., "My previous job was not that bad"), the present (e.g., "I feel exhausted, I can't stand this anymore"), and the future (e.g., "What if things remain like this and I never find another job?"). The past and present often have implications for the future or are used to imagine the future, and an imagined future can make one re-evaluate the present or the past.

Moreover, GDC is generated by an adaptive process that makes sure our goals and needs are met. However, the output of this process can be characterized as adaptive or maladaptive based on its consequences. Rumination and worrying refer more to a maladaptive process: they have no positive influence on the goal discrepancy, have short-term and long-term consequences, and are self-perpetuating as the goal discrepancy is unaddressed. In contrast, GDC such as reappraisal and problem-solving refer to a more adaptive, constructive process that leads the person to change their perception of the goal discrepancy (e.g., "What I thought was a threat is not" or "In the end, this goal is not important to me") or creates a plan to address the goal discrepancy and then execute on the plan (e.g., "If I do this then this, I should get back on track"). Importantly, although GDC such as rumination are often referred to as emotion regulation strategies, they are in fact goal discrepancy regulation strategies, regardless of whether the goal discrepancy relates to a situation (e.g., "I am going to fail my exams") or an emotion or affect (e.g., "I am feeling sad; I shouldn't feel sad, I am being stupid! I have everything I need!"). As Martin and Tesser (1996a, p. 198) put it, "emotion motivates rumination when it informs people of a goal discrepancy, but it is the perceived discrepancy, not the emotion per se, that is the immediate precursor of the rumination".

A relevant cueing context (habit-formation)

As our findings illustrated and in line with previous findings, the second proximal cause of rumination is that it can become a habit of thought, as explained in the Habit-Goal framework (Watkins & Nolen-Hoeksema, 2014). Through repeated learning and practicing of rumination in response to unsatisfactory goal progress, a habit forms. In other words, for rumination to become a habit, it has to be used (1) repeatedly (2) in a specific context (e.g., in bed late at night when feeling tired). Conversely, a protective factor against developing rumination as a habit is if a person implements different behaviors (e.g., different regulation strategies such as problem-solving and distraction) in a specific context. Once rumination is linked to a specific context and has become habitual for that context, it can be triggered without intention or effort by "the relevant cueing context (e.g., negative mood) in the absence of a personally important unresolved goal or of an intention to think about the related concern" (Watkins & Nolen-Hoeksema, 2014, p. 28). What is unclear, however, is whether the response that is conditioned to the cue is rumination or the representation of a goal, or both.

14.2.3 Determinants of an episode of GDC

Factors that will modify the perception of goal discrepancies

Several factors can modify the perception of goal discrepancies, either increasing or decreasing the likelihood that a goal discrepancy is perceived. The characteristics of goals (discussed in Martin & Tesser, 2006; Wyer et al., 1996) can make them more salient, such as where they lie on the hierarchy of goals of the person (e.g., feeling included in a social group might be a more important goal than sticking to our resolution not to drink alcohol), whether there are many means to achieve a goal or not (e.g., considering that giving birth to a baby is the only means to attain the goal of parenthood), or whether there are multiple conflicting goals or parallel goals fighting for attention.

In line with this, the locus of control—the perceived control one has—is also highly relevant as it reflects the perceived means to achieve a goal (or a lack thereof) (Lefcourt, 1981). A lack of perceived control to achieve a desired state or to act in a situation and change it can contribute to rumination. Interestingly, locus of control completely explained away gender differences in rumination (Wanke & Schmid, 1996). Another factor could be negative interpreting bias, increasing the likelihood to perceive ambiguous situations negatively as reflecting a goal discrepancy (e.g., Hertel, Mor, et al., 2014; Hirsch et al., 2018; Mor et al., 2014). Other feedback mechanisms might be at play, such as suppressing one's thoughts, leading to the increased availability of unwanted thoughts, thereby increasing the perception of goal discrepancies (Wenzlaff & Luxton, 2003).

Finally, how attention is deployed plays a role in the perception of a trigger. If people are doing nothing special, their attention can be easily turned to goal discrepancies—the threshold is lower. However, if a person is busy doing an activity, the extent to which attention is occupied by that activity will increase the threshold of perception of a discrepancy. For instance, when one is in a state of flow, one might not notice they are getting hungry unless the hunger reaches a certain threshold of intensity. Similarly, that is why distraction is an effective strategy against rumination: it increases the threshold for the perception of goal discrepancies, which reduces the likelihood of people ruminating. In contrast, certain beliefs or attentional strategies such as monitoring for threat, monitoring for specific thoughts, or 'safety behaviors' may lead a person to be hypervigilant towards certain stimuli (e.g., the occurrence of specific thoughts or bodily sensations) and perceive more easily undesired states (because of a lower threshold of detection). Importantly, the threshold at which another goal can enter consciousness or be perceived depends on the importance (motivational value) of the current active goal (Martin & Tesser, 1996a). Finally, according to this reasoning, only when a person is unconscious will they have a zero chance to engage in goal-directed cognition, as they will be unable to perceive any goal discrepancies.

Factors that will modify the likelihood of rumination being used when a goal discrepancy is detected and how it is implemented

Faced with a goal discrepancy, if people are motivated to address it, they can respond in various ways—rumination is not the only option. Therefore, the choice of ruminating (i.e., to use a specific form of GDC) to regulate perceived goal discrepancies will depend on a variety of factors. One key factor is metacognitive beliefs, which are a key component of the S-REF model (Matthews & Wells, 2004; Wells, 2000; Wells & Matthews, 1996). Metacognitive beliefs specify the personal relevance and coping implications of thoughts (Wells, 2000). Positive metacognitive beliefs will encourage rumination. For example, believing that one can solve their problems by thinking about them and believing that rumination is an effective and desirable coping strategy. Or a person might say they *want* to understand and solve their problems and therefore be more prone to rumination. People might also have negative metacognitive beliefs that reinforce rumination through a sense of helplessness, like "When I start worrying, I cannot stop" (Wells & Cartwright-Hatton, 2004). Self-critical tendencies, as shown in our results and prior research, might also further encourage the use of rumination (Kolubinski et al., 2019). Finally, a lack of knowledge about other emotion regulation strategies can contribute to rumination, as people would resort to what they know best for lack of alternatives.

Then, this choice will inevitably be implemented in different ways. How effective, systematic, or constructive this implementation is, and the content it refers to, will shape the type of thoughts (and their features) that emerge[5]. For instance, depending on the type of processing mode, *constructive / analytical / concrete* versus *unconstructive / experiential / abstract* (Watkins, 2004, 2008; Watkins & Roberts, 2020), the GDC will either be effective or ineffective at addressing the goal discrepancy. This adaptiveness or maladaptiveness will also help define what type of thought we are referring to. Constructive thoughts that navigate between past, present, and future might correspond better to what we call 'problem-solving'. Constructive thoughts about the future in which we try to think of solution to face adversity might be referred to as planning. However, unconstructive thoughts focusing on past and present experiences might be referred to as rumination, whereas unconstructive thoughts about the future are referred to as worrying. What follows, for instance, the act of worrying will define whether it is adaptive or maladaptive. If initial worrying is followed up by planning to prepare for the future, then the act of worrying might be considered adaptive because of its resulting output but if people are just worrying then it is considered maladaptive (see the next section about consequences).

Overview of an episode of goal-directed cognition (GDC)

Figure 29. Episode of goal-directed cognition (GDC)

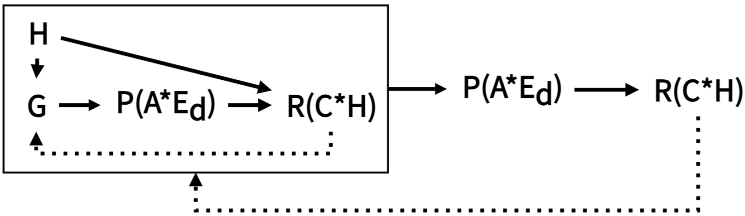
Note. G = active goal representation; H = a conditioned habit; P(Att*Extent$_{discrepancy}$) = the probability of perceiving a goal discrepancy is a function of the attentional state of the person and the extent of the goal discrepancy; R(Choice*How) = the response (how the person chooses to regulate the perceived goal discrepancy) depends on the chosen way to regulate the discrepancy (i.e., 'Choice') and how the chosen regulation strategy is implemented (i.e., 'How'). Importantly, both goal-representations and responses can be activated as habitual responses to specific cues.

Figure 29 illustrates the process of an instance of GDC. At any time, depending on their current active goals (**G**), people can perceive various discrepancies based on a combination of the characteristics of this goal, and based on what they know, past experiences, their perception of the external world, their perception of their physiological state and sensations

[5] Inevitably, these features are ever evolving and influenced by the perception of the person of their attempt at regulating.

(**Extent**$_{\text{discrepancy}}$). The perception of a goal discrepancy (Probability of perception, **P**erception) does not only depend on the extent of the goal discrepancy but also on the attentional state of the person (**Att**). Following this perception stage, if a goal discrepancy enters awareness, the person will regulate this goal discrepancy (**R**esponse or **R**egulation). What the regulation step will look like will depend on the choice of how to regulate (**Choice**) and how the choice is implemented (**How**). The choice of regulation depends on current knowledge/self-knowledge (perceived control, metacognitions, knowledge of regulation strategies), internal context (physiological state) and external context (the external world), and goal-characteristics. A person might choose a behavioral regulation strategy (e.g., distraction) or choose to regulate the goal discrepancy mentally at first, which leads to GDC. These GDC will take up a certain form, certain features, again based on knowledge and context. These features influence the type of thought that emerges[6] ('problem-solving' vs. 'rumination' vs. 'worrying', etc.) and also their consequences, and their (in)efficacy at addressing the goal discrepancy that triggered them. Finally, in case GDC or a goal-representation has been conditioned with a specific cue (**H**), the goal-representation or the GDC can be triggered, starting the regulation process either directly by inducing a response, which then might activate a goal-representation based on current context, or by activating the representation of a goal.

Figure 30. Monitoring of the regulation process



Note. Once a GDC episode is started, it is monitored and can itself be subject to goal discrepancies and regulation. G = active goal representation; H = a conditioned habit; P(A*E$_d$) = the probability of perceiving a goal discrepancy is a function of the attentional state of the person and the extent of the goal discrepancy; R(C*H) = the response (how the person chooses to regulate the perceived goal discrepancy) depends on the chosen way to regulate the discrepancy (i.e., 'Choice') and how the chosen regulation strategy is implemented (i.e., 'How').

The regulation of the goal discrepancy becomes the current focus (the current goal) which is monitored and can itself be subject to goal discrepancies and regulation (see Figure 30). A person might revisit past experiences to try to understand what went wrong and fail to progress on this goal. Their perception of how they are progressing might be biased (e.g., by metacognitions such as "If I do not understand a situation, it is because I have not thought about it enough") which will make them pursue their train of thought longer than is reasonable. If,

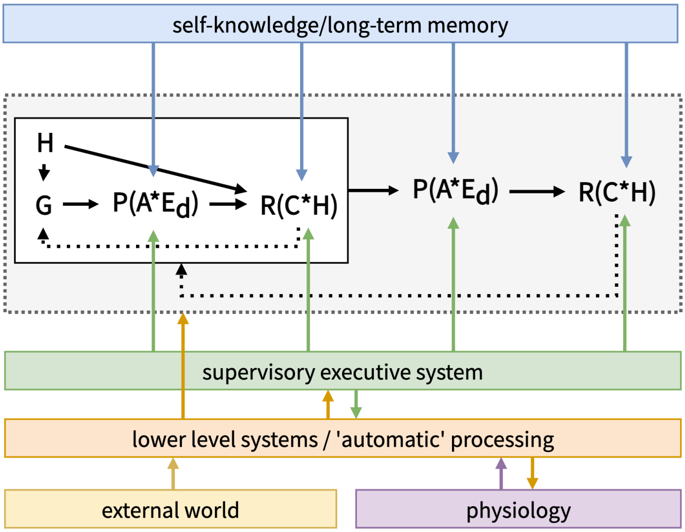
[6] This reasoning is the same as the constructivist theory of emotions (Barrett, 2017): 'emotions' are labels we use to name and describe a combination of internal stimuli and external contextual factors to which a meaning has been attributed. For instance, an upset stomach and a fast heart rate before going on stage might contribute to feeling 'anxious' but could also be interpreted as feeling 'excitement'. Moreover, the association between emotion-label and its manifestation is dependent on the knowledge of the person (which is in part culturally defined).

however, they perceive they are not making progress by ruminating, they could try to choose another way to regulate the initial goal discrepancy. They could distract themselves, act on the situation, change their mind about the goal discrepancy that makes them reevaluate it (e.g., "In the end, I don't care about this job that I didn't get; I will find a better opportunity"), or practice acceptance and letting go of the need to reduce a perceived discrepancy. Importantly, if they choose to distract themselves, the goal discrepancy will still exist, and it might therefore get triggered and perceived again. For instance, if a person is ruminating while in bed, they might try to redirect their attention to their breathing to change their mind. Yet, in this situation, the threshold at which a goal discrepancy can resurface and require attention is very low, as the person might have low motivation to attend to their breathing but very high motivation to deal with the goal discrepancy they tried to distract themselves from. Perhaps in those cases, a person could seek a more motivating distraction, such as listening to an audiobook, or schedule a moment the next day to think about their goal discrepancy, giving them a peace of mind knowing that it will be dealt with.

What breaks a GDC episode? If the goal discrepancy is changed, reduced, or if another goal is activated. The latter can be either caused by external factors (e.g., someone taps on your shoulder and takes you out of your train of thoughts) or by internal factors (e.g., you get a horrible migraine, or you realize you are starving and your stomach is hurting). People will ruminate until they shift their attention to something else (either voluntarily or due to external factors).

As explained in the S-REF model (Matthews & Wells, 2004), this dynamic process is at any time supported by self-knowledge, long-term memory, and a supervisory executive system (Norman & Shallice, 1986). External stimuli or intruding thoughts will activate the supervisory executive if they are motivationally significant, and the central executive will appraise the entering stimulus in regard to personal goals and compute whether there is a discrepancy [**G** → **P**(**A*E**)]. If there is a discrepancy, a search for coping options is executed, and a specific coping strategy is selected, adapted to the current situational demands, implemented, and monitored [**R**(**C*H**)]. The chosen strategy will be implemented, and the discrepancy will be monitored by the central executive until the discrepancy is resolved or attention is diverted. All these processes therefore rely on the interaction between the executive and the self-knowledge level, as both perception/appraisal and coping/regulation need access to self-relevant knowledge (Lazarus, 1999). The perception/appraisal stage computes a discrepancy between the current and desired state and therefore uses self-knowledge as a reference. The person needs access to self-knowledge to choose a coping method to reduce the perceived discrepancy and adapt to the current situation, as specified by skill theory (Anderson, 1982). Of course, in addition to self-knowledge and a supervisory executive system, all of these processes also receive constant input from and are interacting with lower-level systems, the external world, and the body's physiological systems, which send inputs but at the same time support this dynamic process (see Figure 31).

Figure 31. Interaction of the GDC regulation process with other systems

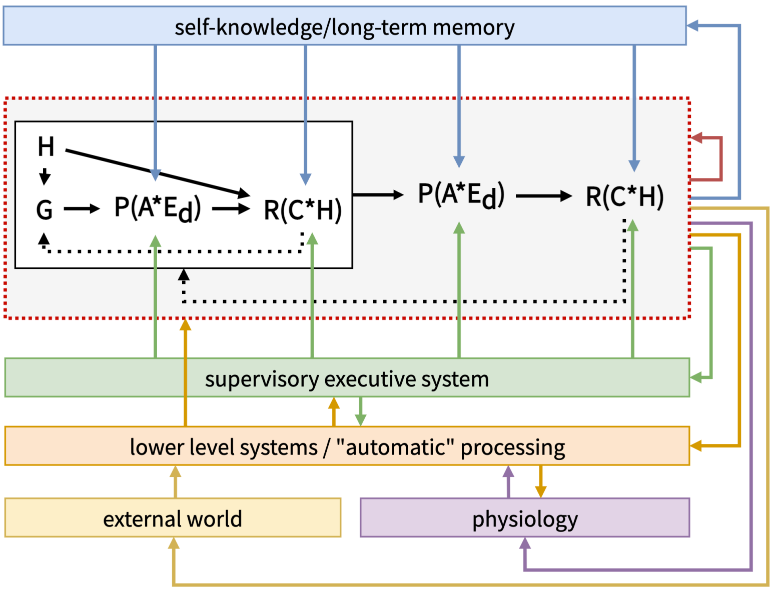


Note. The process of goal-directed cognition (GDC) is continuously influenced by various systems. G = active goal representation; H = a conditioned habit; P(A*E_d) = the probability of perceiving a goal discrepancy is a function of the attentional state of the person and the extent of the goal discrepancy; R(C*H) = the response (how the person chooses to regulate the perceived goal discrepancy) depends on the chosen way to regulate the discrepancy (i.e., 'Choice') and how the chosen regulation strategy is implemented (i.e., 'How').

14.2.4 Emerging properties, aka consequences

All these parameters define the episode of GDC. The above processes generate a variety of behavioral and cognitive consequences in parallel (Wells & Matthews, 1996). In function of these parameters, GDC will have a specific duration and physiological arousal associated with it. This will have short-term and mid-term consequences. Then the frequency of these episodes, taking into account their parameters, duration, and intensity, will have long-term consequences that cannot be tied back to a specific instance of GDC. Instead, it is the cumulative effects of frequent, long, intense episodes of GDC that lead to long-term consequences that unfold more slowly over time but are very real. The feedback loops illustrating the consequences of maladaptive GDC are illustrated in Figure 32 and color-coded to make it easier to navigate the following paragraphs that explain these consequences.

Figure 32. Consequences of GDC represented as feedback loops



Note. A goal-directed cognition episode has a series of consequences which creates several feedback loops on the systems it is influenced by. G = active goal representation; H = a conditioned habit; P(A*E_d) = the probability of perceiving a goal discrepancy is a function of the attentional state of the person and the extent of the goal discrepancy; R(C*H) = the response (how the person chooses to regulate the perceived goal discrepancy) depends on the chosen way to regulate the discrepancy (i.e., 'Choice') and how the chosen regulation strategy is implemented (i.e., 'How').

The direct implications of maladaptive GDC. The first direct consequence is that the low-level processing operations and thus behavior are affected by the chosen coping strategy. The immediate implications of maladaptive GDC, and more specifically, rumination, are that the trigger, the goal discrepancy, is not addressed. This type of cognition can, therefore, easily become repetitive and increase in duration. With unaddressed goal discrepancies, people can ruminate for longer, feel bad for longer, and have negative thoughts for longer. Moreover, maladaptive GDC is used at the expense of more adaptive alternatives and therefore results in perceived impaired problem-solving (Watkins & Moulds, 2005) and interferes with instrumental behavior (Lyubomirsky et al., 2015; Lyubomirsky & Nolen-Hoeksema, 1993; Nolen-Hoeksema, 1991; Nolen-Hoeksema et al., 2008; Watkins & Moulds, 2005). For instance, GDC might stop a person from falling asleep, contributing to sleep problems.

Impact on self-knowledge and long-term memory. GDC, particularly when maladaptive, not only disrupts present-moment awareness but also shapes long-term self-perceptions and memory. This iterative process has several key consequences. First, they can maintain maladaptive metacognitive beliefs. For example, a person may develop the belief that their thoughts are uncontrollable or that to solve their problems, they should mentally think about them for really long stretches of time (Matthews & Wells, 2004). Second, GDC can engrain negative experiences into one's memory, increasing the likelihood of these negative, self-referent memories resurfacing (Wells & Papageorgiou, 1995) and maintaining a negative mood state over time (Nolen-Hoeksema, 2000). Third, GDC can solidify self-views. Repeatedly processing negative self-referent information can entrench negative self-beliefs, affect one's self-esteem and self-concept in the long run, and create a biased autobiographical memory that favors the recall of negative events. This process might also feel 'rewarding' through self-verification: if people have a negative view of themselves and have negative thoughts about themselves, then these thoughts might be self-reinforcing as they confirm their view of themselves (Giesler et al., 1996; also discussed by Nolen-Hoeksema et al., 2008; North & Swann Jr, 2009; Talaifar & Swann, 2020). This can lead to an identity centered around being, for example, a 'ruminator', someone who 'overthinks' or someone who lacks control (i.e., an external locus-of-control, which is a perception of having no ability to influence events or circumstances; Lefcourt, 1981), further inhibiting personal growth and adaptation. Such metacognitive beliefs, incubation of negative experiences, biased self-view, and autobiographical memory can perpetuate a cycle of disempowerment, reinforce maladaptive regulation strategies, and reduce attempts to manage goal discrepancies constructively.

Impact on the supervisory executive system. For this part, I want to distinguish between GDC's impact on bottom-up processes of the supervisory executive system and top-down processes involving what we referred to in this thesis as executive control. First, GDC cognition could influence bottom-up processes. Given that GDC maintains a negative mood, it could narrow attentional focus (e.g., Clore & Gasper, 2000). Whitmer and Gotlib (2013) postulated in their 'Attentional Scope Model of rumination' that negative affect reduces the attentional scope by constraining the range of information available in working memory or from long-term memory, thereby increasing the chances of rumination. Therefore, negative affect facilitates rumination by narrowing the attentional scope, and rumination further contributes to negative affect. However, beyond the valence of affect or emotional state, it might just be the motivational state that matters. In line with this, a state of interest narrows attentional scope in comparison to a neutral state or a state of awe (Sung & Yih, 2016). And this is not the only study suggesting that positive affect narrows attentional scope. In reviewing the literature on attention scope, Lacey et al. (2021, p. 188) conclude: "Experiencing affects low in motivational intensity encourages attentional broadening [9], while experiencing affects high in motivational intensity encourages attentional narrowing [2]". This ties back nicely with the previously discussed results that show that dopamine stabilizes information in working memory (Cools, 2008; Gruber et al., 2006; Watanabe et al., 1997). All of this suggests that GDC may bias bottom-up processing by narrowing attentional scope because people are motivated to engage in GDC, which in turn contributes to maintaining currently active GDC.

Second, GDC might impact top-down executive processes. Given what I discussed previously regarding the resource depletion account vs. resource allocation hypothesis, I do not think that rumination (or other types of GDC) depletes cognitive resources; 'depleting' is not the right term to use. Indulging in GDC might drive resources away from other processing tasks, which might translate into a disruption of attention. However, this does not mean that the executive system is impaired or that resources are depleted—its resources are just not 'efficiently' allocated. Cognitive and attentional resources cannot be depleted, but instead we can only allocate what we have until our resources are fully taken: "Whenever the demand for resources exceeds the supply, performance will suffer and decisions must be made about where to allocate the available resources" (A. Johnson & Proctor, 2004, p. 290). This explains why rumination negatively affects performance on a wide range of tasks, including recruiting executive control (Philippot & Brutoux, 2008; Watkins & Brown, 2002) but also tasks requiring more broadly concentration and learning (Lyubomirsky et al., 2003).

Hence, in line with Section 14.1.1 on reexamining the resource depletion account, GDC does not deplete resources and resources do not get depleted over time—instead GDC occupies cognitive 'bandwidth'[7]. The bandwidth at any point in time is limited. When GDC cognition uses the whole or part of that bandwidth, less is available for other tasks. This has the interesting implication that an important individual difference might be people's executive control abilities, and more specifically, their available 'bandwidth' at any time. Research on task-unrelated thoughts has explored this idea. For instance, people with higher working memory capacity had more task-unrelated thoughts during undemanding tasks compared to people with low working memory capacity (Levinson et al., 2012). Conversely, this is why distraction is such an effective regulation strategy to counteract GDC: good distraction, in which people *want* to indulge in, fully occupies their attentional bandwidth, thereby leaving none for GDC.

Impact on lower-level systems. By practicing negative cognitions, GDC reinforces negative interpretation biases, increasing the likelihood of perceiving goal discrepancies in the future. These interpretation biases would act automatically and influence how people perceive events or internal stimuli, such as physiological sensations (Hirsch et al., 2016). Moreover, GDC can also backfire by increasing the strength of negative associations between self-related concepts and events (Bargh & Tota, 1988).

Impact on the external world. GDC interferes with the external world indirectly by promoting maladaptive patterns of interaction with the external world. For example, using maladaptive GDC as a regulation strategy prevents people from learning more effective skills, such as being able to correctly regulate emotions or profit from social interactions with others. Moreover, maladaptive GDC might also indirectly reduce social support (Nolen-Hoeksema & Davis, 1999). For instance, although emotion sharing can help social connections, it can also elicit negative feedback from the outside world (e.g., venting repeatedly might push away other people).

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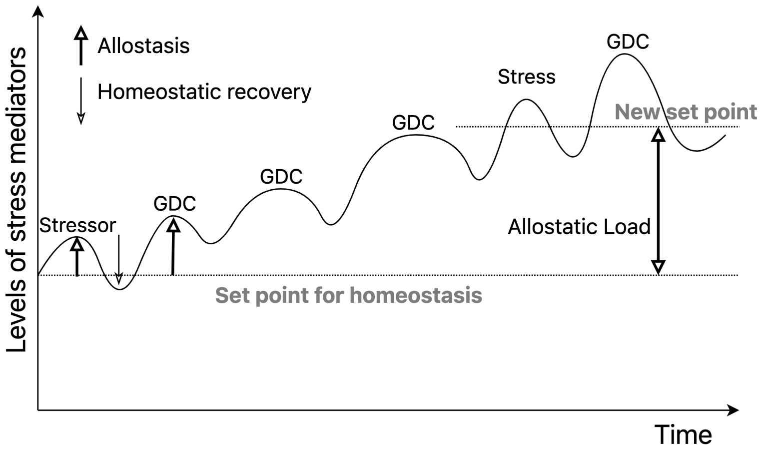
[7] As a side note, I think we should get rid of the 'resources' metaphor of executive/cognitive/attentional processes as it only perpetuates the implicit assumption, popularized by research on the (mostly debunked) 'ego depletion' effect, that we have 'resources' that can be depleted and need to be restored. Instead, the term 'capacity' is more appropriate, but it is used interchangeably with 'resources'. Another option is to use the term 'bandwidth' and associate executive abilities to a metaphor of, for example, internet connection. We would not 'consume' working memory/cognitive/attentional 'resources' (as seen, for instance, in Levinson et al., 2012) but we would *use* a part of our working memory/cognitive/attentional *bandwidth* or *capacity*.

Impact on physiology. According to all the previously discussed parameters, GDC instances will last a specific time and will be perceived as repetitive, reoccurring thoughts about psychological problems, fears, worries about the future, etc. This repetitiveness is an emerging property of a maladaptive regulation process, which in turn becomes the cause of a range of somatic health problems. Indeed, the more a person engages in GDC, the more they repeatedly activate a cognitive representation of one or more psychological stressors (cf., the perseverative cognition hypothesis; Brosschot et al., 2006; Ottaviani et al., 2016). This repeated cognitive representation is accompanied by physiological responses and sustained activation of the body. This is akin to a prolonged state of action readiness for the individual (Dalgleish & Power, 2000; Frijda, 1988; Lazarus, 1991).

The sustained activation of cognitive representations of stressors associated with the sustained activation of the associated physiological responses lead, over time, to long-term consequences for biological systems, including autonomic, endocrine, and cardiovascular functions (see Chapter 1.6., 'Rumination and physiology: the perseverative cognition hypothesis'). It does so by keeping a state of physiological stress active longer than is healthier or than it would stay active if it were left alone.

This process relates to the concepts of allostasis and allostatic load (McEwen, 2017). Allostasis refers to the range of adaptive and systemic processes that are activated by the brain in response to the perception of a stressor. This allostasis occurs through various mediators, "not only cortisol and adrenalin but also the parasympathetic nervous system, pro- and anti-inflammatory cytokines, and metabolic hormones. Moreover, the brain uses interacting mediators to alter neural circuitry and functions" (McEwen, 2017, p. 551). These same mediators, although useful and adaptive in short bursts, can lead to detrimental consequences when they are overused and dysregulated (D. Lee et al., 2014). This is referred to as the allostatic load; it is when the set point for homeostasis has been moved towards a state of constant dysregulation. In brief, GDC disrupts homeostatic recovery and increases the allostatic load over time (see Figure 33).

Figure 33. Allostasis and homeostasis in response to GDC



Note. A graph representing the effect of stress and GDC on the levels of stress mediators in the body. GDC = goal-directed cognition. This graph has been adapted from Lee et al. (2014).

This allostatic load model of the effects of GDC illustrates how the cumulative physiological activation induced by stress over time serves as the primary mechanism underlying the adverse somatic health effects of GDC. These adverse effects correspond to, for example, inflammation (Moons & Shields, 2015; for a review, see Szabo et al., 2022), impaired immunity (Brod et al., 2014; D'Acquisto, 2017; Reed & Raison, 2016), and worse physical health and chronic health conditions (Curhan et al., 2014; Leger et al., 2018; Seiler et al., 2020). However, the health effects of allostatic load are not specific to GDC, as allostatic load can be caused by other factors too (for a review of the health effects of allostatic load, see Guidi et al., 2020).

Relating this back to state and trait rumination, it is possible that episodes of maladaptive GDC repeatedly trigger allostasis, which over time increases allostatic load. Therefore, the tendency to have maladaptive GDC could be an indirect indicator of the allostatic load of a person. This might explain an additional part of why trait rumination and person-level means of state rumination predict depression and anxiety (Chapter 10): the higher their tendency to ruminate, the more they disrupt homeostasis and increase their allostatic load. To really test this hypothesis, measures of rumination should be better able to capture the duration of the thoughts (it is somewhat captured by 'repetitiveness', but not very precisely) in addition to their intensity (captured by 'negativity' or which could be capture by a measure of physiological stress, such as heart rate variability). Interestingly, beyond just the person-level means of rumination features, the inertia of negativity might be a good indirect indicator of how much allostasis a person is going through: if a person has high negativity inertia, it indicates that they experienced negative thoughts continuously between measurements.

14.2.5 Measures

An advantage of this prototheory is that it makes it easy to organize measures of GDC thoughts and processes involved in GDC. Some examples are given in Table 23.

Table 23. Non-exhaustive overview of possible measures for GDC processes

Processes	**Measures**
Self-knowledge/memories	Metacognitive beliefs (Wells & Cartwright-Hatton, 2004) Self-esteem (Robins et al., 2001) Autobiographical memory/recall biases (Everaert et al., 2014) Self-criticism
Potential for goal discrepancies	Self-discrepancies (Hoebeke & Philippot, 2019; Philippot et al., 2018) Adverse life events (Hawes et al., 2021) Goal-characteristics and how they are valued (e.g., Verkuil et al., 2015)
Current goal discrepancies	Negative affect Negativity of thoughts Explicit measures of goal discrepancies
Low-level systems	Interpretation bias Associative tests
Supervisory executive system	Attention bias Working memory capacity Executive control tasks
Physiology	Hair cortisol Cortisol Heart rate variability Blood pressure Allostatic load (Buckwalter et al., 2011; Carbone et al., 2022; Whelan et al., 2021)
Goal-directed cognition/regulation strategy choice and implementation	Questionnaires of worry, rumination, repetitive thoughts Emotion regulation questionnaires

14.2.6 Underlying circuitry

Alterations in the neurological and biological aspects that are underlying all of these processes (hormones, brain networks, neurotransmitters…) would also affect all of the previously described processes. The most direct example is the allostatic load model and how repeated activation of stress responses can modify the underlying circuitry. Other interesting aspects beyond the neurological basis of these processes could be, for instance, the role of dopamine. As GDC is a motivational process, dopamine seems like an interesting element to integrate into a theory of GDC, either to lead to novel insights or to help distinguish between wrong and correct inferences about research results. Other factors, such as sleep deprivation or poor nutrition, might also affect our body systems, thereby modulating the processes involved in GDC. For instance, sleep deprivation might lead to bodily sensations that can be negatively interpreted or to mood-congruent negative cognition by activating negative self-knowledge or memories. Sleep deprivation might also affect one's executive control, thereby leading participants to experience a slowing in everyday tasks, which might not be what they want, thus creating goal discrepancies they can ruminate about. They might therefore have temporarily worse executive control and be less efficient in choosing alternative coping styles, resisting urges and cravings, and resorting to their most automatic behaviors. These behaviors might, in turn, create feelings of guilt, further fueling goal discrepancies and maladaptive GDC.

14.2.7 The role of executive control and the association with trait rumination

In the previous sections, I discussed how executive control enables GDC (Levinson et al., 2012; Matthews & Wells, 2004). We saw, for instance, how state rumination might interfere with performance by occupying cognitive bandwidth (see Section 14.1.1). However, research has often focused on the associations between executive control and trait-GDC, such as trait rumination. Given the many factors at play in GDC, I thought it would be interesting to highlight a few alternative explanations for the correlations found between executive control and trait rumination:

- People who have worse executive control abilities have a slower processing speed or might have a smaller working memory capacity. Therefore, their problem solving might be less effective, which can result in thinking for longer, which contributes to rumination.
- There could be mediating variables that affect both executive control and rumination, and that, when unaccounted for, give the false impression that rumination and executive control may be causally related. For instance, adverse life events or lower social and economic status. On the one hand, adverse life events and adverse life situations, such as poverty, have been linked with poorer executive control (e.g., Mani et al., 2013). On the other hand, these situations can be perceived as goal discrepancies, thereby feeding GDC.
- In line with this, when we find that executive control predicts trait rumination X years later, it is not proof that executive control affects rumination in everyday life. Perhaps *because* people have poorer executive control, they are less able to face adversity or do well in life, which gives them more discrepancies to ruminate about.
- Perhaps studying rumination in people that have weaker or no executive control could help understand its links with GDC better. For instance, given that children's executive control abilities mature over the course of several years, do children ruminate more as they age (as their executive control abilities develop) or less, controlling for the other factors in play in ruminating? And what about older people? Do they ruminate more or less as they age, as their executive control abilities weaken, controlling for the other factors in play in rumination?

14.2.8 The future of a unified theory of GDC

This section aimed to provide a preliminary sketch of a unified theory of rumination and related thought processes. I used our reconceptualization of rumination as a multifaceted, dynamic construct and our results as a starting point and combined them with key elements from previous models, including the Goal-Progress Theory (Martin & Tesser, 1989), the S-REF model (Matthews & Wells, 2004; Wells & Matthews, 1996), the Habit-Goal framework (Watkins & Nolen-Hoeksema, 2014), and the Perseverative Cognition Hypothesis (Brosschot et al., 2006). It highlights how all these theories can be combined into a unified theory of not only rumination but of 'goal-directed cognition'. I was also inspired by the Extended Process Model of Emotion Regulation (Gross, 2015) in how to lay 'flat' the dynamic process of how GDC arises, why it takes a specific form, how long it lasts, and what ends a GDC cycle. The proposed theory therefore elucidates the multifaceted and dynamic nature of goal-directed cognition highlighted in this thesis, mapping its triggers, determinants, emerging properties, and widespread consequences. While not an exhaustive theory nor a 'new' theory, it offers an integration of previous theories and an organizational structure to guide future research and hypothesis testing.

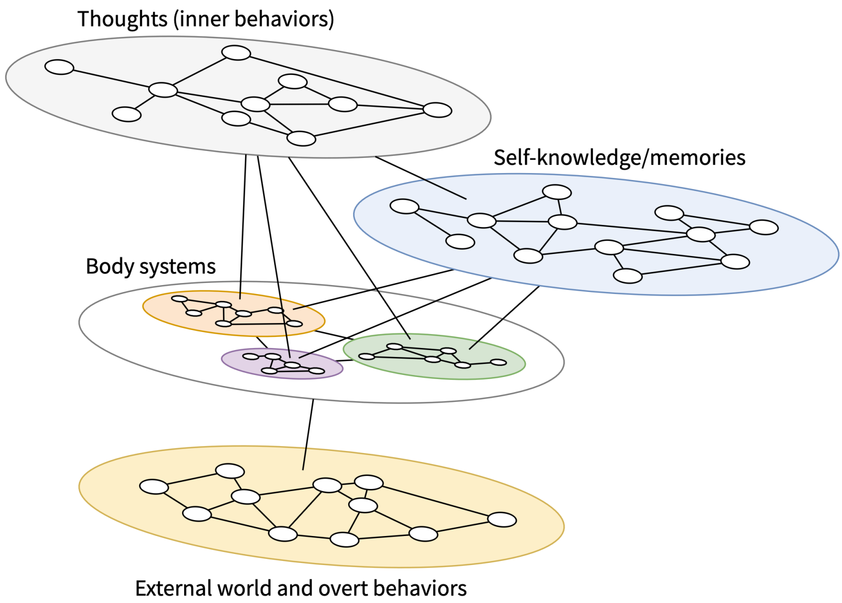
This prototheory serves as both a map and a compass—it guides the integration of empirical findings within a structured framework and directs future research endeavors. It underlines the complex interplay between state and trait manifestations of rumination and other GDC, reminding us that what we conceptualize as trait rumination is, in fact, the emergent result of these multifactorial interactions. Moreover, by elucidating the within-person state processes of GDC, it provides a lens for generating targeted interventions while furthering theoretical models.

As it is a prototheory, inevitably, shortcuts and simplifications have been made. The future of this prototheory lies in its evolution into a fully-fledged theory, one that can be formalized through mathematical modeling (Borsboom et al., 2021). Such a theory would encapsulate the probabilistic nature of GDC, detailing its emergence, manifestation, and persistence alongside its psychosocial and physiological consequences. There is much to be detailed, and even further extensions could be made by integrating more clearly the latest theories of emotion (i.e., the constructivist theory of emotion) and the notion of active inference and predictive processing, according to which our brain predicts and constructs our experiences (Barrett, 2017).

14.3 A final note on rumination as a network and the limitations of the network theory

Reconceptualizing and measuring rumination as a dynamic network of interacting components indeed led to new insights, as we postulated. However, the features we investigated only pertained to features of thoughts. As the GDC theory highlights, features of thoughts are only one part of the ruminative process. They are important—the content of thoughts matters. Yet, only accounting for these features means studying only one piece of the puzzle. Each component of the GDC theory could be viewed as a layer of networks (see Figure 34). For instance, body systems enable thoughts and self-knowledge, which we could refer to as 'emerging properties', and these emerging properties in turn affect the body systems. From this perspective, we only studied two layers: the features of thoughts (inner behaviors) and a small part of the body layer (i.e., executive control).

Figure 34. Multilayered view of goal-directed cognition



Note. This image illustrates how all the systems involved in goal-directed cognition (GDC) and goal-directed cognition itself could be represented and conceptualized as multilayered interacting networks.

However, the 'network' metaphor could be reconsidered too. It might not be the best metaphor to approach how human psychology works: 'networks' and 'nodes' that can be 'targeted', with researchers studying how interventions affect how 'connected' nodes are or whether targeting the most 'central' node is effective. This can cause science to become vague and convoluted. For instance, networks do not allow the representation of moderation effects. And it would have been too vague, unnecessary, and complicated, or too convoluted, to create a network GDC theory.

Moreover, it is not because results from analyses can be best viewed as graphs (e.g., mlVAR or multivariate transfer entropy) that the best metaphor to explain the results is a network. As said by Erickson, "the network metaphor often creates artificial objects and makes us think we have been precise when we have been vague" (Erickson, 2012, p. 1). This is a criticism we could make of the network theory of psychopathology and the network theory of rumination. The 'network of psychopathology' became its own entity, with researchers arguing that we can 'intervene' on the network or on specific nodes. Yet, to date, this view has not given the breakthrough it promised, apart from embracing the heterogeneity of mental disorders such as depression (separating the label 'depression' from its heterogenous causes).

Perhaps the metaphor of networks could be replaced or combined with other concepts. To use a term from the philosophy of biology, recent research has served to highlight how disorders such as depression are *homeostatic property clusters* (Boyd, 1991). Instances of depression share common properties but do not have all the exact same properties (Fried & Nesse, 2015a). These properties are all somewhat related and maintained through homeostatic mechanisms. These mechanisms ensure that the cluster remains relatively stable over time. To use a term from the philosophy of the social sciences, depression can also be viewed as a *social construct*. Social constructs are concepts, categories, or practices that exist because they are agreed upon and maintained by societal or cultural consensus rather than due to any inherent, objective, or natural characteristics. They are a product of our world, culture, and human interaction, and in turn shape the world we live in (e.g., the fact that we celebrate mothers on 'Mother's Day' and fathers on 'Father's Day'). Finally, to use a term from physics and psychology, depression can also be viewed as an *emergent property*. In the same way social constructs shape our environment and our environment reinforces the social constructs, emerging properties such as mental states (i.e., emerging from complex interactions enabled by our bodies, brain included) affect the underlying circuitry. This principle is called 'supervenience'. The principle of emergence refers to how local interactions among agents (in my example, different body systems) give rise to self-organized structures, such as thoughts (Holland, 1995). Supervenience refers to how emergent properties, such as thoughts, influence the behaviors and actions of lower-level agents (El-Hani & Emmeche, 2000).

Clusters, social constructs, and emergent properties such as depression and rumination are commonly studied by researchers, either to be explained, predicted, or used to explain or predict other constructs. Sometimes these homeostatic property clusters/social constructs/emergent properties are used as objects, as 'real' entities, either out of facility or because people do associate them with something real. All of this then influences theory, research, interventions, everyday language, and public policies.

Hence, metaphors and concepts are not to be taken lightly. It is crucial to (1) be aware of how metaphors and concepts can guide or bias research and our interpretation and (2) recognize that they serve a purpose. By being aware of those two points, researchers can move away from seeking to use a single metaphor or theory to explain phenomena and instead combine metaphors based on pragmatism. Concretely, rumination, worrying, major depressive disorder, and general anxiety, can be used because of their purpose, such as enabling people to say, "I ruminate too much" or asking for refunds from the healthcare system for therapy for 'major depressive disorder'. In contrast, researchers could talk about 'goal-directed cognition' or directly describe the properties of a specific instance of major depressive disorder, the general term being too vague, leading to misunderstandings. One purpose at the societal level is to provide health care, whereas the purpose in research would be to understand and explain.

Lastly, I do not have an answer to whether the network metaphor is useful—it depends on many factors. I also do not have an opinion on what better alternatives there are. All of this is to say that it is best to question our underlying assumptions and the impact they have on how we view the world. As the Youtuber Philosophy Tube succinctly puts in her video *Social Constructs (or 'What is a woman really?')*: "Depending on how we describe problems, different solutions might present themselves. When we talk about social constructs, the implication is that the constructs aren't fixed. We could change stuff that we project onto the world if we wanted to". What I did in this thesis and theoretical section was to zoom out, question underlying assumptions, and frame the problem of understanding rumination and related concepts differently. I hope that in the future, researchers will continue to seek a more nuanced and flexible approach to the study of psychological phenomena. This could involve embracing complexity, questioning assumptions, and considering the purpose and implications of their theoretical models.

Chapter 15.

Methodological implications

A central contribution of this thesis is demonstrating the synergistic value of using diverse research methods and analyses to study the complex phenomenon of rumination. By collecting both experimental and intensive longitudinal data on the same multifaceted rumination measures, important insights emerged from comparing results across studies. For example, uncovering trait-like aspects of certain rumination features in both laboratory and daily life settings. While using the same sample of participants in both investigations can be seen as a limitation, it enabled these informative cross-study comparisons that may not have otherwise been as straightforward with separate samples.

Building on the empirical findings, in this section I discuss key methodological implications that emerged through this research approach. First, I elaborate on the benefits of combining multiple complementary analysis methods, as illustrated by the chapters of Section 2. Next, I highlight the importance of multi-method research, integrating both controlled experiments and intensive longitudinal data collection in daily life. Additionally, I propose the potential utility of developing a taxonomy categorizing measures, manipulations, and analyses in this field. Lastly, I offer a brief commentary on notions of causality relevant to psychological research.

15.1 Combining multiple methods of analysis

A limitation of this thesis and a threat to the generalizability of the results is the fact that the two types of data collected (i.e., from ESM and from an experimental study) come from the same forty participants. It also reduced the potential power to detect small effects. We did, however, have enough power to detect medium to large effect sizes, for instance, in Chapter 10, based on post-hoc power analyses.

Yet, these very limitations also enable the strength of this thesis. Using the same participants in two different data collections enabled us to gain insights not only from the results but also from the comparison of the results across research methods and methods of analysis. For instance, it was insightful to uncover the trait-like nature of negativity and self-criticism across two different types of data collections. And comparing the results between mlVAR and multivariate transfer entropy analyses also allowed us to better interpret the results, highlighting differences and similarities between the analyses.

Hence, the implications for future research are twofold. First, researchers should be encouraged to analyze the same data with different methods of analysis. This would help improve research because different methods of analysis have different assumptions and can therefore take into account different effects or be biased in different ways. Finding the same results across methods of analysis with different assumptions and statistical properties could help increase confidence in the results. It would even be interesting to have these analyses done within the same paper; however, the potential length of such a paper might be a limitation to its publication. Moreover, the idea of using different methods of analysis to account for their different assumptions and biases has already been discussed under the name of 'multiverse analyses' (Steegen et al., 2016). A multiverse analysis consists of automatically varying all the different parameters of statistical analyses in order to explore the influence of researchers' choices about these parameters on the results. This 'multiverse analysis' could be adapted to compare results from different methods of analysis. Moreover, multivariate analysis could be combined with sensitivity analyses such as the cross-validation methods we used in Chapter 10 to avoid overfitting with smaller sample sizes.

15.2 Studying rumination

The results and the new outline of a theory of GDC have implications for studying rumination. If the goal is to study the effects of rumination in everyday life, then unitary measures of rumination might be enough. Similarly, if the goal is to study the effects of rumination longitudinally or describe its prevalence among disorders or its associations with different variables (e.g., heart rate variability), then a trait measure of rumination as a unitary construct might also be enough. However, even in those cases, measuring the different components of rumination will give more insights and will help not only describe rumination in more detail but also lead to a better understanding of rumination, in the same way studying rumination as a multifaceted construct in this thesis has led to interesting insights. If the goal is to better understand rumination, then researchers should definitely study all its components (or as many as possible) or make specific hypotheses regarding the influence of each component. For instance, if we improve executive control during a single instance, what will be the effect of that improvement controlling for baseline executive control? Or, for example, does improving executive control only affect the repetitive nature of rumination (i.e., people ruminate less either because they think 'better' or are able to implement more easily alternative regulation strategies) but not the negativity of thoughts (i.e., the underlying goal discrepancies and their perception).

Moreover, different types of measurements might give different types of insights exactly in the same way as different methods of analysis can: by involving complimentary, or at least different, biases. For instance, although using state measures with the experience sampling method allows for the reduction of biases such as recall bias, this recall bias might in itself be a useful explanatory variable (as discussed in the GDC theory section). A state measure would capture (a) the variable intended to be captured, (b) a response bias, and (c) a small recall bias depending on how big the time window is (i.e., a state measure about the last 30 minutes would involve a smaller recall bias than a measure about the last four hours). In contrast, a trait measure would capture (a) the variable intended to be captured, (b) a response bias, and (c) a recall bias. This recall bias itself is involved in mental disorders such as depression (Colombo et al., 2019, 2020; Horwitz et al., 2023). Lastly, a way to measure recall bias would be, for example, to compute a recall bias index based on the difference between state measures of rumination and trait measures of rumination. However, it would require the items to be exactly the same to not add additional confounds to the analysis; only the timeframe would change. Behavioral measures of rumination could also be used to compute a recall bias. Concretely, one could conduct a study in which participants (a) are asked to press a button every time they ruminate, (b) asked to answer state measures of rumination about the last four hours (e.g., "How much did you ruminate in the last four hours"), (c) daily measures of rumination (e.g., "How much did you ruminate today?"), and (d) trait measures (i.e., "How much did you ruminate this week or these last two weeks?" or "How much did you ruminate this past month?"). This data could be used to compute indexes of recall bias, which could then be used as a predictor of, for example, depression symptoms. Although such a study might increase awareness of thoughts, which should somehow be accounted for, it might be a great way to study recall bias or test whether participants' recall bias is influenced by their more recent experiences. If the study lasts a month, is the overall perception of how much they ruminated more strongly associated with the last week or last few days than the first days or first week of the measurement period?

15.3 A taxonomy of possible research

All these ideas led me to the conviction that it would be useful for rumination research, but also for other variables, to have a 'taxonomy of possible research'. Given that, depending on how rumination is studied and measured, different components of it might be captured, a taxonomy of research could potentially help structure results and guide their interpretation. Such a taxonomy of ways to study rumination could also include the implications of different statistical analyses and methods of intervening on rumination or the target variable, and how these parameters influence the inferences researchers can make. I give an example of such taxonomies in Table 24 and Table 25.

Table 24. Taxonomy of measures for rumination and executive control

	Rumination		**Executive control**	
Measure types	Self-report	Behavioral	Self-report	Behavioral
State/ momentary measures	*In the moment…* *During the last five minutes…* *During the last four hours…*	Breathing task during x minutes Tapping on a button whenever one ruminates	*In the moment…* *During the last five minutes…* *During the last four hours…*	Short behavioral task (e.g., computerized task on smartphone) Longer behavioral task
Daily	*Today, …*	—	*Today, …*	NA
Trait	*Last X weeks…* *In general…*	—	*Last X weeks…* *In general…*	Longer tasks and test-retests measures?

Table 25. Taxonomy of manipulation and intervention methods for rumination and executive control

Rumination		Executive control	
State	Trait	State	Trait
Inducing rumination (e.g., versus distraction)	–	Temporarily inducing improvements or impairments: through pharmacology, coffee, lack of sleep, exercise, neuromodulation	–
Therapy (i.e.,one should notice changes over time in both state and trait rumination, but the effects might take time to be noticed or can only be noticed on certain components involved in GDC, but not all).		• Executive control training • Repeated neuromodulation sessions • Repeated sports/exercise regiment • Better nutrition/sleep routine	

Note. This table illustrates how manipulations that aim to change trait rumination or executive control affect the construct at both the state and trait levels whereas manipulations that aim to change state rumination do not necessarily induce change at the trait level.

For instance, rumination could be measured using a brief state measure (i.e., "Are you ruminating now?" or "Were your ruminating in the last ten minutes?"), as a state measure over a longer timeframe (i.e., "How much have you ruminated in the last four hours?"), or as a daily measure (i.e., "How much have you ruminated today?"). As people ruminate before sleeping or in the middle of the night when they cannot sleep, one way to assess rumination would be to ask participants about it the next morning. This might be more affected by recall bias, but at least it would not perturb participants' sleep. This data would then need to be processed before doing statistical analyses. Indeed, even though the measure happens in the morning, it refers to data regarding the night before. Then there are the trait measures that could refer to either the past week, the past two weeks (most common), any arbitrary period, or ask "In general… how much do you ruminate?", which is probably the most subject to biases.

Beyond questionnaires, rumination could also be measured behaviorally once (e.g., a 30 sec continuous state measure using a joystick; Wade et al., 2021) or across the day (e.g., by tapping a button or a beeper every time one ruminates). Perhaps researchers could ask for third-party observed data, but this might be especially complicated in the case of rumination and not always feasible (e.g., if a person has a partner they live with, researchers could ask: "How much do you think your partner ruminates?"). The same thinking process could be applied to executive control.

Moreover, these measures could be used in different research designs (see Table 26). Either cross-sectional research, longitudinal research, intensive longitudinal research, or experimental research. And, within these methods, the studied variables could be influenced in different ways. For instance, rumination could be influenced through therapy (e.g., Feldhaus et al., 2020), through an intervention targeting one's life circumstances (e.g., G. Nelson et al., 2020), or through executive control training (Onraedt & Koster, 2014).

All these factors are important to consider for two reasons. First, they influence the data and results obtained and the hypotheses one can test. Second, they also clarify data summaries by giving a broad structure to generalize results and phenomena and can help structure narrative, systematic, and meta-analysis reviews. For instance, such a taxonomy should make it clear that one cannot interpret the results of longitudinal data and intensive longitudinal data in the same way.

Table 26. Taxonomy of types of research

Frequency of measurement	Measurement type	Time period	Resulting type of research
Once	State measure	5-10 minutes	Experimental/cross-sectional
Several times	State measure	Several measurements a day for several days	Intensive longitudinal study
Several times	Daily measurement	Measurements for several days	Daily intensive longitudinal study
Several times	Trait measure	Once a week	Longitudinal
Once	Trait measure	e.g., "last two weeks"	Cross-sectional/correlational
Several times	Trait measure	e.g., every month for a year or once a year for several years	Longitudinal (importantly, the broader the timeframe between measurements, the more likely it is that covariates can affect results).

To help study and measure phenomena better, another aspect to include (or that theory should include) is specifying the expected time resolution of change of variables and whether we can influence this variable (i.e., how malleable it is). For instance, state affect of a person might be easier to change than their autonomic system (with proxies of it such as heart rate or heart rate variability). Indeed, one could change their state affect as simply as by listening to one's favorite energetic and feel-good song or by doing a quick bout of exercise. However, changing heart rate variability might require sustained efforts (e.g., Groß & Kohlmann, 2021; Routledge et al., 2010, p. 77). All of this of course depends on whether we are expecting the change at the state level or at trait level. For instance, it might be possible to change state affect easily, but changing one's tendency to be in a positive affective state might involve many more parameters and require more effort. Similarly, state executive control could be affected by medication or natural substances such as coffee (Kim et al., 2021). But trait executive control changes might require long-term efforts through, for example, executive control training. The effects of executive control training (controlling for sleep, nutrition, exercise, coffee intake, etc.) might only become visible at the state and trait level after a certain number of training sessions and elapsed time. Moreover, a caveat of studies on executive control and rumination, and specifically studies on the effect of executive control training on rumination, is that the training could reduce rumination through indirect pathways, given that executive control is involved in many behaviors of daily life. For example, improved executive control might help participants better navigate their daily life by working more efficiently and therefore feeling less stressed, and thereby ruminating less.

The parameters of the methods of intervention might themselves have an impact on the efficacy of the intervention and must be considered. For instance, tDCS involves so many different parameters, from the type of montage, the intensity, and the duration to the behavior of the participant during stimulation and their physiological or state parameters (scalp thickness, motivational state, …). It is not enough to say that tDCS has an impact on rumination; such a statement is too broad. Instead, we should arrive at a point in which we can say that tDCS with X montage and with X intensity during X minutes positively impacts executive control after stimulation in people with lower executive control, controlling for scalp thickness or brain parameters. And, in the same way trait rumination captures a combination of rumination plus a recall bias and a response bias, the efficacy of an intervention can be dependent on the parameters of that intervention plus a placebo or nocebo effect (Corsi & Colloca, 2017). Therefore, if effective, researchers could consider using the placebo effect or combining tDCS with encouraging specific beliefs about tDCS, in the same way believing that stress is beneficial can help optimize stress responses (Crum et al., 2020).

15.4 A note about causality

A final methodological implication and limitation of this thesis pertains to causality. Causality is a loaded term that has led to many philosophical and epistemological debates (Ross, 2023). The notion of causality is useful in several ways. First, it is used when we give causal explanations when we seek to understand a phenomenon. Second, it is also useful to predict. If we know the causes of an effect, we can use this information to predict outcomes. A third utility of causation is that it allows for control. In psychology, we are concerned about causation because we not only want to understand our psychology, but we also want to be able to control it, for example to improve the mental health of patients. Fourth, causation is useful because it helps determine responsibility (e.g., who is to blame in a car crash).

There are several definitions of causation. These definitions are important because they help to distinguish causes from non-causes by agreeing on a set of hallmark features of causation. However, defining causation is not enough, because in science, and particularly in the life sciences, we encounter different *types* of causation that definitions of causation alone do not completely encapsulate. In her talk, Ross (2023) gives examples of how, in the life sciences, we distinguish between (a) structuring causes from triggering causes, (b) specific causes from non-specific causes, and (c) proximal/direct (close to an effect) from distal/indirect causes (further in the causal chain from the effect). She also talks about how causes can be organized in different ways or how they can be described in different ways. Distinguishing between all these types of causes is important because these different types of causes imply different ways of understanding effects but also give different types of control over the world.

The most common view of causation in psychology research is the interventionist view (Woodward, 2003, 2007, 2023): X causes Y if manipulating X leads to changes in variable Y. This is, for example, the type of causality we investigated in Chapters 11 and 12 of this thesis. However, in Chapters 8 and 9, we also made causal inferences, but from a different kind, by relying on a different definition of causation concerned about prediction: Granger causality (Granger, 1969). A variable X is said to 'granger-cause' variable Y if information from past values of X helps to predict values of Y beyond the information contained in the past of value Y. This is, in essence, what we examined by looking at temporal associations between variables using time series analyses (i.e., multivariate transfer entropy).

Such time-series analyses can be best used in an exploratory manner, as we did, to uncover potential causal relations, as they satisfy at least the basic feature of causality, namely temporal precedence. However, in psychology, we are not only interested in predicting but also in intervening. We could assume that no psychological intervention can be precise enough to only target a specific variable. Thus, instead of lamenting or debating on that aspect, we could instead embrace that feature of psychological interventions and test it by seeing whether the combined effects of intervening on plausible causes affect these causes more so than 'targeted' interventions (see, Section 16.1.1). A next step could thus be to use methods such as multivariate transfer entropy with all the variables involved in GDC and an intervention that targets those variables. Indeed, it is possible to do network comparisons either between subjects or within subjects using multivariate transfer entropy; see https://pwollstadt.github.io/IDTxl/html/idtxl_network_comparison.html.

Chapter 16.

Clinical implications

The multifaceted analysis of rumination dynamics in this thesis not only advances theoretical understanding but also points towards potential clinical implications. In this section, I discuss several clinical considerations that emerge from the empirical and conceptual work of this thesis. First, I explore how our results suggest ways existing therapies could be used to target specific rumination features and its motivational roots. Next, I examine implications for interventions targeting executive functions like tDCS. I then propose that intensive longitudinal measurements could help personalize treatments by identifying individual causal patterns. Lastly, I acknowledge the limited generalizability of our clinically healthy sample but suggest our theoretical developments may inform future clinical applications. While much work remains to translate these foundational insights into clinical practice, they highlight the potential utility of multidimensional, contextualized models of cognition for elucidating new treatment strategies. By embracing complexity, future research can move towards more precise, personalized interventions that get to the heart of maladaptive goal-directed cognition such as rumination.

16.1 Targeting features of rumination

Our results suggest that two features in particular, negativity and self-criticism, drive the other features of perseveration, replaying, and, to a lesser extent, brooding. Interestingly, they also exhibit trait-like patterns and are less context-dependent. In contrast, perseveration, replaying, and brooding seemed more context-dependent.

Based on these results, we could therefore hypothesize that negativity and self-criticism are two important therapeutic targets for intervention. As said previously and articulated in the Goal-Directed Cognition theory, negativity could be a proxy for goal discrepancies. That is, people have negative thoughts because they think about a situation that does not correspond to their ideal state or ideal situation (past, present, or imagined future situation). The components influencing this perception of goal discrepancies are (1) the external world (in contrast to the 'internal world'), the real situation, (2) how it is perceived, (3) the attentional component of GDC, and (4) people's goals.

This gives a therapist four levers through which to reduce rumination. These levers are already part of existing therapies. For instance, behavioral activation is one of the most effective interventions for depression (Cuijpers et al., 2007), and rumination a key symptom involved in the onset and maintenance of depression (Nolen-Hoeksema et al., 2008). As depressive people are often stuck in a rut, they do not make any progress towards their goals. It therefore makes sense that one of the most efficient interventions for depression is behavioral activation. Although it is possible to reduce repetitive thoughts through cognitive therapy, putting depressive people in motion and inciting them to act seems to be the most direct and effective way to do so. Perhaps it is because behavioral activation actually helps them make progress towards goals, thereby targeting the most proximal cause of rumination. Moreover, behavioral activation can induce cognitive change or make it easier: people would create evidence against their beliefs through their actions, which can make it easier to learn new, more adaptive beliefs, alone or with the help of a therapist. Indeed, instead of thinking one's way into feeling confident, it is best to act despite limiting beliefs, because those behaviors and exposition can support real self-belief change. Thus, behavioral activation targets the external world[1] component involved in GDC.

However, sometimes the external world cannot be changed because goal discrepancies are either in the past (and therefore immutable), in the future, or in the eyes of the beholder. Changing the external world might also not be enough if other factors strongly contribute to a person's ruminations. For instance, one may ruminate because their life is falling apart, and their rumination could then be considered to be mostly caused by their life circumstances (although, even in misery, some people can be happy by changing their perception). In contrast, a person who has objectively fewer problems or adversity in their life could ruminate as much or even more than the previous person because of their goals, their perception of reality, or self-knowledge (e.g., meta-cognitive beliefs). In those cases, to reduce the 'goal discrepancy' part, to reduce negativity, psychotherapists could target the other components, for example, how a patient perceives things, their ability to direct their attention (e.g., distract themselves), or their goals (e.g., defining more adaptive, flexible, attainable goals). All these components are targeted in therapies such as the Unified Protocol (Barlow et al., 2020), Acceptance and Commitment Therapy (Hayes et al., 2012), or meta-cognitive therapy (P. L. Fisher, 2021). These types of therapies therefore target how the external world is perceived, target goal discrepancies (e.g., by working on the values of a person and their goals), and how goal discrepancies are perceived.

Regarding self-criticism, we can assume it is probably part of the self-knowledge of a person, their goals for themselves, and a rigidity in how to achieve them. People prone to self-criticism would more easily perceive discrepancies. Targeting this specific feature by training people to be more self-compassionate might reduce their perception of goal discrepancies, leading to fewer negative thoughts and the need for rumination. Research results already illustrated the role of self-compassion, with increases in self-compassion leading to better therapeutic outcomes (e.g., Kazemi et al., 2020).

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[1] Changes in the external world also help to explain sudden changes in the life situations of patients that lead to the sudden recovery of depression: important goal discrepancies that were at the root of a person's depression, a main theme for their ruminative thoughts, suddenly disappear.

Theoretically, by targeting these two features in this way, people should naturally start having less negative and self-critical thoughts. As a second-order consequence, based on our results, they will spend less time ruminating, and they will replay fewer events mentally. Additionally, they could also learn alternative regulation strategies or gain new knowledge through psychoeducation, leading them to wonder less about the causes and consequences of their feelings or events (i.e., less 'brooding').

Regarding the potential habitual nature of rumination and GDC, new contingencies should be practiced replacing the old habitual responses. For instance, if a person says they often ruminate when they are tired, feeling down, or sick, they could create a new habit replacing rumination by implementing and practicing a new rule of how to act: "When I feel X, I will not ruminate. Whatever I was thinking about, I will plan a moment in the future, when I feel better, to think about it. Now, I will instead rest or distract myself by engaging in rewarding activities". Of course, this might not be easy for everyone. It might require some practice, but it can be effective. A new habit is created contingent on rumination: "Whenever I ruminate, I wonder if I could be tired or just feeling bad". Later, it could evolve into a completely new habit by replacing the rumination habit. Practicing this new rule, 'not ruminating when feeling tired', in addition to overriding a habitual response, also avoids the mood-congruency effect that contributes to seeing things more negatively (Gaddy & Ingram, 2014).

Lastly, mindfulness interventions could be used to target the executive/attentional component of goal-direction cognition. Mindfulness encourages people to pay attention to internal and external events purposefully and nonjudgmentally (Bishop et al., 2004; Kabat-Zinn, 2015). Mindfulness training helps people gain awareness about their thoughts and become better at reorienting their attention away from these thoughts to an arbitrary target such as one's breathing, which can help to stop the ruminative process (Heeren & Philippot, 2011b; Segal et al., 2018; Teasdale et al., 1995). Importantly, a meta-analysis of mindfulness-based interventions for the treatment of depressive rumination suggests that it is effective at reducing rumination (Perestelo-Perez et al., 2017). Moreover, mindfulness training might not only reduce rumination via a better ability to reorient attention but also by fostering self-compassion, thereby targeting the self-critical tendencies that contribute to negative thoughts (Svendsen et al., 2017).

16.1.1 Causality, 'fat-hand', and clinical interventions

Although the previous section highlights various target for clinical interventions aimed at reducing rumination, these interventions should not be viewed as targeting a single aspect of rumination. Psychological interventions are unlikely to be specific enough to target a single cause. Instead, they are best viewed as 'fat-hand' interventions. The term 'fat-hand' has been used to describe interventions that influence many causes at once (Eronen, 2020). For example, exercise can improve executive control (Furley et al., 2023) but also improve energy levels (Miles, 2007) and autonomic function (Soares-Miranda et al., 2014). It can also lead to psychological benefits such as increased confidence or social connection (i.e., in the case of group sports). Given that rumination and GDC more broadly seem to be examples of 'many causes, many effects' (Ross, 2023), it might be ineffective to target a single cause. Therefore, this 'fat-handed' aspect of psychological interventions might be a useful feature.

However, fat-handed interventions are problematic for causal inference. Indeed, as discussed by Eronen (2020), it is not possible to test claims such as X causes Y with fat-handed interventions. If I take the example of executive control training, a researcher cannot claim with certainty that by training executive control and noticing an effect on trait rumination, worse executive control causes rumination. This is because other variables could have been impacted by executive control training, such as a person's performance on common daily tasks or at work. This variable could explain the changes in trait rumination, as people would have fewer things to ruminate about. Although this is a simple example, it illustrates how according, to the Woodwardian interventionist view of causation (Woodward, 2003), "X is a cause of Y (in variable set V) if and only if it is possible to intervene on X to change Y when all other variables (in V) that are not on the path from X to Y are held fixed to some value" (Eronen, 2020, p. 2). Given that it is impossible to maintain fixed all the potential psychological variables involved or affected by psychological interventions, it is impossible to use psychological interventions to test causal claims.

In addition to this limitation to causal inference in psychology, Eronen (2020) also highlights other threats to causal inference. Overall, he paints a bleak picture of the possibility of ever establishing causal relationships with psychological causes. He highlights two key implications. First, that researchers should develop methods and formal tools to better understand fat-handed interventions. Second, he recommends adopting a broader perspective regarding causal inference. Robust evidence for causal relationships would be derived not from single instances of strong evidence of a causal relationship but from many independent sources of evidence: "Such evidence can lead to a high degree of confidence even if the sources are individually relatively weak in their evidential strength (Eronen, 2015; Kuorikoski & Marchionni, 2016; Munafo & Smith, 2018; Wimsatt, 1981; 2007)" (Eronen, 2020, p. 6).

I believe that one way to better deal with fat-handed interventions is to move away from single hypotheses and embrace complex and integrative theories, such as the one I attempted to construct. Formalizing such theories would lead to a clear framework for testing interventions. Moreover, I believe the two ideas I discuss in Chapter 17 could help regarding the second point made by Eronen (2020) about the role of cumulative evidence.

16.2 Should executive control be a treatment target?

The results of Chapters 11 and 12 showing the limited effects of tDCS on rumination align with the mixed findings from prior literature, suggesting isolated neuromodulation may have restricted potential for targeting rumination. However, these null results should be interpreted cautiously given the limitations of our work—the lack of a clinical sample and examining healthy executive control. Moreover, the theoretical reconceptualization proposed in Chapter 14 provides additional reasons for prudence regarding executive control interventions.

Enhancing executive capacities alone without addressing the intrinsic motivational roots of rumination may inadvertently reinforce repetitive negative thinking patterns, as it could reinforce people's ability to ruminate.

This notion that improving executive control might have counterproductive results has also been voiced in the literature on executive control training. Indeed, Hoorelbeke et al. (2022) found that the association between increased rumination and increased disruption of future affective states became stronger over time following executive control training. As the authors put it, "increasing cognitive control may have detrimental effects when these regained cognitive resources are used to more strongly engage in maladaptive emotion regulation strategies and/or other dysfunctional behavior (e.g., based on positive metacognitions regarding rumination)." (Hoorelbeke, Van den Bergh, et al., 2022, p. 15). This interpretation is completely in line with the links I made so far with rumination, the S-REF model, executive control, and tDCS. It is not sufficient to only improve executive control. To ensure these newfound cognitive resources are used to implement adaptive coping strategies, patients should learn and practice these coping strategies.

Overall, though, the cost-benefit of using tDCS or executive control training might not be worth it given the small effects, if there are any. Unless clear deficits or impairments are found at baseline, which we did not test or control for in our tDCS study, it is probably more ethical and sensible to target all the other factors involved in GDC first. Moreover, even if there are executive control impairments, therapists should first verify that basic needs are met, such as sufficient sleep, good nutrition, and enough physical activity.

Yet this does not preclude a possible role for adjunct executive interventions like tDCS and cognitive training if combined judiciously with approaches targeting underlying drivers. TDCS interventions and executive control training should be best viewed as treatment augmentation, not as standalone interventions (Van Den Bergh et al., 2018). Indeed, tDCS's best use case might not be to improve executive control but instead as a tool to improve neuroplasticity and learning (Ripoll Rozisky et al., 2016). Though evidence is presently mixed, with some studies showing no added benefit (e.g., Ferrari et al., 2021; Van Den Bergh et al., 2020), improving executive control and modulating neuroplasticity and learning during therapy focused on establishing adaptive habits remains a promising avenue. Patients could potentially practice regulating emotions and overriding rumination urges during active tDCS stimulation under a clinician's guidance. Nonetheless, extensive further research in clinical groups is required before newly developed conceptual models highlighting rumination's contextually multifaceted nature can be translated into refined treatment strategies.

In summary, while our work does not support executive control interventions in isolation, it underscores the vital need for nuanced dynamic theories accounting for the intricacies of cognition to inform the development of comprehensive intervention paradigms. By embracing complexity, future efforts may uncover ways to address the various components of goal-directed cognition.

16.3 Identifying key intervention targets

Our results illustrate how intensive longitudinal data, in combination with our methods of analysis, could help identify important intervention targets. In this thesis, we only studied rumination and executive control, but future research or endeavors to monitor therapeutic practices could involve several other variables: physiological ones (e.g., sleep, nutrition, exercise), self-knowledge ones (e.g., metacognitive beliefs), and other overt behaviors and regulation strategies. In doing so, patients could be monitored for two weeks or a month even before starting therapy. With that data and adapted methods of analysis, therapists could perhaps more easily tailor the therapy to the patient. Moreover, ESM could be used for monitoring the recovery of patients with a combination of metrics such as person-level means, standard deviations, and the inertia of important variables. Physiological parameters could also be integrated into this monitoring system and could help detect shifts in people's mental health or detect early warning signals that could help implement just-in-time interventions or preventions (Wichers et al., 2016).

A limitation of this is the potential amount of data required. Maybe in the future, mixed approaches could be used. Once the main causal pathways have been formalized, replicated, and generalized to different types of populations, only observing which causes are most 'active' in participants lives would help direct the therapy without the need for extensive data collection.

An approach that is already being used, which is less data-intensive, is process-based case conceptualization (Philippot et al., 2019). This approach consists of combining the self-reported experiences of the patient with results from questionnaires and the theoretical knowledge of the therapist. By combining all this information, patient and therapist collaborate on a schematic representation of the patient's life and, more specifically, the processes involved in their difficulties. Through this approach, they could start targeting one or several processes, adapting the case-conceptualization over time based on new insights.

To conclude this section, although the clinical implications of this thesis are limited given our use of a community sample, they still open up useful perspectives for future research. Reconceptualizing rumination led to various theoretical implications, such as a sketch of a unified theory of goal-directed cognition, which could offer a framework to understand and design interventions. Future research could test whether the multifaceted approach to rumination, or the Goal-Directed Cognition theory, can help be used to nuance case conceptualizations for other goal-directed cognition than rumination.

Chapter 17.

Broader implications for the field and beyond

When one stays at a general abstract level of understanding of the literature, they get the broad picture and even a sense of understanding. However, this picture may show some cracks and loose ends once one zooms in on the details. This discussion has sought to do this when going into the theoretical, methodological, and clinical implications. I highlighted the complex associations between executive control and rumination, emphasizing nuances in understanding these connections and proposing avenues for future research. In doing so, I realized that many of the nuances I wanted to discuss had already been explored in past, often forgotten, research. Moreover, the research supporting these nuances, or the research supporting old and newer theories, is often scattered and not well documented or organized. Several new theories arise, being created in parallel, with a high chance of being forgotten over the years.

Exploring the research on rumination and executive control led me to the conviction that the scientific process in psychology is flawed (Eronen & Bringmann, 2021; Oberauer & Lewandowsky, 2019). There are problems of generalization, replication, and theory construction. Importantly, the fault does not reside only in the humans conducting the research. Instead, it is the current research practices, in combination with the ever-growing stream of information and research publications, that are maladaptive. The way research is currently published, evaluated, built upon, and evolves shows the limitations of our human nature. We are limited in our ability to make sense of complex data. We are biased. Or we simply do not have the time and the mental bandwidth to keep up with the continuous stream of new research. Research happens and gets published in a sort of parallel processing fashion, with several researchers working on the same or similar topics but not always being aware of related research on their topic. Moreover, new theories are constantly being published or proposed without always explicitly building upon previous theories (e.g., the HEXAGON model including six different processes, but other processes involved for example in the S-REF model, such as the role of meta-cognitive beliefs), sometimes because previous theories were not specified enough, were just a hypothesis, or were not formalized.

Several solutions have already been proposed to improve the scientific process. Great strides have been made in open science, with an increasing number of researchers sharing their code and data. However, other aspects of the scientific process could still be improved. I will explore two complementary ways in which we could create better scientific processes based on a new view of conducting literature reviews and building theories and on readily available and free tools. These solutions could transform the scientific process in psychology by better leveraging our strengths and using technology to compensate for our limitations.

17.1 A first solution: evolutive collaborative literature reviews

The aggregation of data and research findings in science is highly inefficient. Often, by the time a meta-analysis or a systematic review is published, it is already, in a sense, outdated. The only way to update these reviews would be to start the process all over again. I experienced this firsthand with the systematic review we conducted. There is currently simply no other way to update this systematic review than to go through the same process again, republishing an updated version. The content of this systematic review would greatly overlap with the first systematic review. The same holds for meta-analyses. If one wants to redo a meta-analysis published a few years ago, they might have to start the process all over again, especially if the authors of the previous meta-analysis are unreachable and have not shared their data openly.

I believe a streamlined process for evidence and data aggregation should avoid researchers repeating past works (only correcting or verifying past work when necessary). Researchers should be able to collaborate asynchronously on data and evidence aggregation and on the interpretation of these data. Technology should be able to save time at as many steps as possible in the review process. Moreover, never again should there be multiple meta-analyses published at the same time or worked on in parallel without two research groups knowing the existence of the other research group conducting a similar meta-analysis or systematic review. This is a waste of resources. The only benefit is the multiplicity of method choices and interpretations. But to reap these benefits, we do not need two meta-analyses on the same topic. Collaborative efforts among researchers in data collection, aggregation, and statistical analysis could significantly enhance the robustness and reliability of the scientific process, consequently improving the quality of results. The interpretation and implications of these results could be done in separate papers. In this way, the objective information would be contained and separated from the interpretation the researchers make, which is admittedly entirely subjective and can create more noise than signal.

What I would propose and will detail in a future paper is a process and infrastructure to conduct 'Evolutive collaborative literature syntheses.' First, whenever a researcher wants to start a review, for instance, a systematic review of the effects of tDCS on rumination, they could verify on a platform whether such a review has already been done or is currently ongoing, using keywords such as 'tDCS', 'rumination', 'repetitive negative thinking', etc. If one does not exist, then they could start the process of creating one. If one already exists or is ongoing, they could join the review process. The idea would be that anybody should be able to collaborate at any time on ongoing review efforts. Technology could then help automate certain aspects of the review. For instance, it could automate the analyses, such as by using markdown R scripts that would automatically be able to recompute the results of a meta-analysis every time a new study is added. Technology could also help by automatically extracting data from research papers, enabled by the progress in artificial intelligence. Lastly, such collaborative efforts could then be combined with taxonomies of research methods such as the one I discussed in the 'Methodological Implications' chapter; this would allow researchers to structure reviews based on the possible combinations of research methodologies and measures.

This evolutive, collaborative, 'in-the-open' process has already been accomplished with great success for open-source software. It is open source because anyone can view the code of the software, but also because anyone can suggest edits to the code to fix bugs or extend features. Different mechanisms are in place to keep up with a history of edits, manage conflicts, and manage versions of software. Contributions are fully transparent and updated in real time.

The full translation of these mechanisms into a literature review would require a more extensive explanation, but the core idea to remember is that it would allow for avoiding doing work twice (e.g., extracting data from papers), collaborating asynchronously over time, and following the evolution of results through different versions of a review. By making the review process continuous and open, reviews will constantly evolve. Based on different criteria, such as a yearly frequency or 'every five studies', with the code and data visualization being automated, a new version could automatically be created and stamped with a version number and a date. Authorship (contributions) would be automatically computed. The results would be clear and easy to read, as the publication would focus on all the objective parameters and results. The interpretation would be done separately. Every time a new version of a review is automatically published, researchers are prompted to interpret their results and contrast their interpretations with those of others. In summary, the promise of an evolutive collaborative method is to allow for better and asynchronous collaboration, the pooling of efforts, a gain of time and resources, greater clarity, separating the objective/process-based aspects of the literature review process from the subjective/interpretation aspects, faster iterations, and perhaps also collaboration for the interpretation of the results.

17.2 A second solution: evolutive theory construction as software development

When coding in R or Python for statistical analyses, it is essential to specify the packages your code relies on. Achieving code replicability involves not only mentioning the package names but also detailing their versions along with the version of R. These packages are also referred to as 'dependencies' in software development. Given a code, one needs to have the right dependencies to arrive at the same conclusions as the initial publisher. The information about these dependencies ensures a replicable result each time one runs the code, be it software or data analysis code. Sometimes bugs can be found in the code or software, in which case they are updated, and a new version is attributed to the software. Sometimes bugs can be found in dependencies, in which case these dependencies must be either replaced or upgraded to the latest version that solves the bugs, and the code must be adapted if needed; this leads again to a new version of the software. Software development is therefore a highly replicable process. If you have ever submitted a bug to a software company, you might know that one of the first things you need to report to get help is the version number of the software. Without this, it would be impossible to replicate the bug. Moreover, one would not conceive of sharing code online without specifying the versions of their dependencies; it would be considered inefficient, even crazy, and a waste of time for people who would like to use your code or replicate its results.

This well-documented process can be contrasted with theory-building in psychology (and perhaps in science more broadly, though I will focus on my field of expertise). Psychological theories are often created by one or several researchers, and the only way for them to share their theory is to publish it as a research article in a scientific journal. Before the internet, dependence on publishers was essential. Fortunately, nowadays, one can simply share their theory as an openly available preprint. Such a theoretical paper is a mix of exposing the components of the theory, their causal relations, and the evidence for these causal relations. Often, these theories lead to the development of measures. Consider a scenario where we have a theory (T1) accompanied by a corresponding measure (M1). Imagine now that the researchers wish to update their theory based on new findings. Their only option is to publish a new paper explaining Theory T2. However, due to randomness or a lack of virality or popularity, T2 does not get the credit it deserves. Yet, T1 is still being highly cited! Researchers citing T1 might not even be aware of T2, because there is no direct link between the research paper on T1 and the publication of T2. Now, this process gets even more convoluted when other researchers create new theories, either building on parts of previous theories or creating new theories from scratch. However, because they seek to gain time, they test their theory with measures developed based on previous theories. They use, for example, the argument of 'using the most cited measure to ease comparison between results', using measure M1 to test theory T32. However, the underlying assumptions, components, and causal relations of T1 and T32 might be completely different. Measurement M1 might, therefore, not be the best way to test T32. In essence, sometimes new theories are tested with old measures based on old theories, and this might lead to false inferences or biases in the results.

Another limitation of current theory-building is the fact that theories rely on assumptions that are taken for granted and therefore not always made explicit. For instance, the emotion theory of Paul Ekman conceptualized a limited set of emotions as natural, universal kinds (Ekman, 1992). Initial research supported this view, but it was later found that the way the theory was tested was biased. Certain assumptions were ingrained into the testing methodology, which biased results towards finding support for the theory. Once new methodologies were adopted, Ekman's theory was debunked (Barrett, 2006). New theories arose as a result (Barrett & Westlin, 2021).

Similarly, in this thesis, we examined the resource depletion account of rumination. In the way this hypothesis on the association is formulated and discussed in research papers, it carries assumptions such as the fact that we have cognitive 'resources' that can be depleted. However, I explained in previous sections that this assumption was fallacious. Moreover, such an assumption, unless questioned, taints the glasses through which we interpret findings, leading to a self-perpetuating cycle of wondering whether rumination depletes or does not deplete cognitive resources instead of questioning the fact that we have cognitive resources to deplete.

Using software development parlance, I would say that many theories and hypotheses in psychology do not specify all their dependencies (i.e., underlying theoretical assumptions), that sometimes their dependencies contain bugs, and that even though researchers do specify the dependencies of their theories, changes in the dependencies are not automatically detected and do not automatically lead to a reevaluation of the theory.

Lastly, with scientific papers being immutable and literature reviews taking up considerable time, there is no easy way to assess the available evidence for or against a hypothesis or a theory. There is also no easy way to know whether a theory has been abandoned or superseded by a new theory. Citations are somewhat of a measure of popularity, but they are not a direct measure of quality or of how the hypotheses and predictions of that theory have stood the test of time and research studies. What we must avoid in the future is what happened with depression and so many other phenomena. So many hypotheses have been put forward to explain depression. Yet, little work has been conducted to try to contrast or integrate all these hypotheses into an updated theory (see Figure 35, on the next page). Moreover, there is no easy way to assess the empirical validity of hypotheses, that is, whether they are supported by research findings or not.

I experienced all of this firsthand while doing my PhD and writing this thesis. This experience, combined with my interest in software development, has led me to the following idea: researchers could develop theories by using a software development approach. Free tools and software already exist to make this possible (e.g., GitHub and Obsidian). Again, I will not detail the intricacies of how existing software or tools can be used to process what I describe, for sake of brevity.

The core features of the process have already been explained in the previous part about literature reviews. First, theories could be evolutive and live outside of research articles and journals. By relying on open-source practices combined with versioning, there could be a single place on the internet that would contain all the versions and iterations of a theory, with a history of all the changes and a history of the contributors to these changes. When citing a theory, you would refer to a unique name, perhaps a webpage, and a version of the theory (e.g., "S-REF model, v1.2., 2004"), in the same way as one would cite software. Measures could be related to a version of a theory. Hence, whenever a theory undergoes a major revision, it will prompt, at a minimum, a reevaluation of existing measures based on the changes in the theory. Second, the components of a theory, if they rely on other theories or rely on a set of assumptions to be met, could be explicitly listed with a version and could link to their own webpage. For instance, if one were to create a theory of emotion regulation, they might have to specify how they define emotions or at least explicitly state which emotion theory underlies that theory to avoid any ambiguities or misunderstandings. If they later realize that the emotion theory they relied on has been falsified, it will automatically prompt a reevaluation of the emotion regulation theory. Third, causal relations between components of theories could have a code associated with them, or at least a name. New studies could specifically state which associations they test, and data aggregation could be automated based on this data. It would therefore enable us to more easily aggregate evidence regarding a theory as well as the specific causal relations postulated in that theory. All of this would be enabled by open-source software development processes that have been battle tested over the years, fostered world-wide collaboration, and led to the creation of impactful software (e.g., Linux, Python, Blender, etc.).

Figure 35. Depression hypotheses

Year	Hypothesis
1957	Neurophysiological Adaptive Hypothesis of ECT
1958	Cholinergic Hypothesis of ECT
1960	Seizure Hypothesis of ECT
1962	Serotonin
1965	Norepinephrine
1972	Polygenic Networks
1972	Cholinergic, Cholinergic Adrenergic
1972	Receptor
1973	Early Integrative
1970	Neuroendocrine
1978	Serotonin revisited
1980	Hypothalamic Peptide Release
1983	Anticonvulsant Hypothesis of ECT
1984	Critical Interval Hypothesis
1986	Melatonin Hypothesis
1987	CNS Adaptations to Antidepressant Treatment
1987	Phase-shift Hypothesis
1988	Social Zeitgebers and Biological Rhythms
1986	Receptor
1990	Glutamate
1995	Immune/Cytokine
1997	Limbic Cortical Dysregulation
1997	Molecular and Cellular Hypothesis of Depression
2001	Signal Transduction
2003	Network/Connectivity
2003	Brain Network
2006	Neurotrophic/Neuroplasticity
2007	GABA
2008	ROS/ROSG (Reactive Oxygen Species/cGMP)
2009	Inflammatory and Neurodegenerative
2008	Brain Morphology
2009	Neurocognitive Hypothesis
2010	Social Signal Transduction
2010	Dynorphin
2011	Brain Energy Metabolism Hypothesis
2011	Signaling
2012	Translational
2013	Functional Imaging Drug Effect
2022	Microglia Activation
2022	Increased CRF Neuronal Activity

Note. A compilation of hypotheses regarding causes of depression. Compiled by George Dawson and shared on Twitter (Dawson, 2022). Reproduced with permission.

These two ideas—evolutive collaborative reviews and theory-building—are complementary and will benefit from each other. By making reviews easier and more evolutive, it makes it easier to assess evidence for theories, and it therefore makes sense to have theories that can evolve, or at least be openly available and documented. By making theory-building evolutive, collaborative, open, and more structured, and by documenting research based on this theory as it gets published, it would make evolutive review efforts more meaningful. Such methodologies would build upon the open science movement, as papers that are not openly available might not be integrated into evolutive reviews or as evidence for evolutive theories.

Moreover, perhaps such a dynamic will lead researchers to reevaluate their research methods based on their research objectives. For instance, if their goal is not to describe phenomena but to understand and explain them, they might stop conducting correlational research as it does not inform about causal relationships and therefore provides little to no support for existing theories. They might instead focus on fewer publications but of higher quality and impact by focusing on interventions, experimental research, or intensive longitudinal research.

I strongly believe that if such processes were established 20 years ago, the research landscape on rumination would look completely different today. Research efforts would have been more cumulative and iterative, and consequently, the current scientific knowledge about rumination would be richer, more nuanced, and more trustworthy. However, that hypothesis remains to be tested—hopefully in not-so-distant future research.

17.2.1 Embracing nuance in the face of information overload

The landscape of scientific research is increasingly defined by a paradox: the scarcity of time against a backdrop of informational abundance. There is insufficient time to assimilate the vast volume of published research and the wealth of information to which we are exposed, let alone to make sense of it all. Previously, when information was a rarer commodity, it was more manageable. Today, however, we are overloaded by an ever-growing stream of information (e.g., of scientific publication). Faced with time constraints, our brains inevitably cut corners. Our brains are ill-equipped to process and integrate such a multitude of disparate information streams effectively. Compounding this issue is the growing consensus within psychological science that a shift away from reductionist approaches toward a framework that embraces complexity is necessary. Yet, engaging with complexity demands a thorough exploration of nuances, a process at odds with the pressing constraints of time.

Therefore, on the one hand, there is a need for nuance and for embracing complexity, and on the other hand, there is a limited amount of time. The two ideas I discussed arose from thinking about this dilemma and possible solutions. They are two possible solutions to help researchers gain some time, which could be dedicated to embracing greater nuance.

Chapter 18.

General conclusion

This thesis aimed to advance the understanding of rumination and its associations with executive control by addressing how rumination is conceptualized, measured, and studied. It highlighted how, up until now, rumination had mainly been studied as a unitary construct and how the most used research practices did not study rumination as a dynamic fluctuating construct despite theoretical models emphasizing this aspect. In this thesis, we therefore conceptualized and measured rumination as a multifaceted and dynamic construct and explored its associations with executive control through this new lens. By employing a multi-method approach combining neuromodulation and intensive longitudinal data collection in daily life, along with complementary analysis methods, we uncovered novel insights into the complex nature of rumination and its relationship with executive control.

Our findings highlight the influential role of the negativity of thoughts, likely reflecting unresolved goal discrepancies, in driving other features of rumination. Self-criticism also emerged as an important component that may exacerbate the perception of discrepancies. A clear differentiation appeared between content-related features like negativity and self-criticism and process-related features like perseveration and replaying. The former exhibited trait-like patterns, while the latter appears as the result of a failed goal-regulation process. Across analyses, rumination features predicted subsequent impairments in executive control, providing support for the resource depletion account while casting doubt on the impaired disengagement hypothesis. Lastly, our findings call into question the use of tDCS as an intervention to reduce rumination.

Although the empirical contribution of this thesis is limited by its data collection, this thesis' key contribution lies in its methodological and theoretical implications. The results clearly show that there is much to be gained in studying rumination as a multifaceted and dynamic construct by using multifaceted measures and intensive longitudinal research designs. This rich data can then be analyzed in several ways. Indeed, this thesis illustrates how the same multivariate intensive longitudinal data can be analyzed using different methods, yielding complementary insights. In combination with previous research and theoretical models, our empirical findings provided the foundation to establish a blueprint for a new theory of 'goal-directed cognition' that could encompass not only rumination but also worry and related thought patterns. These theoretical developments emphasized embracing the multifaceted, dynamic complexity of cognition. They also prompted a re-examination of the relationships between rumination and executive control processes. The outline proposed incorporates multiple mechanisms discussed in previous theories and maps rumination's triggers, moderators, and widespread consequences within a coherent framework. Such a theory provides a compass to guide future research and clinical applications.

While limited in generalizability due to the non-clinical sample, the clinical implications emphasized targeting the motivational roots of rumination through specific features like negativity. The findings suggest the potential need for combining executive control interventions with techniques that address the core aspects of goal-directed cognition, although research is necessary to establish the effectiveness of such an approach. By discussing the clinical implications of this thesis, we also surfaced fundamental questions about causality and effect that have not only implications for therapeutic interventions but also prompt researchers to reevaluate how they study and seek to establish causality in psychological research.

In conclusion, this thesis illustrated how rumination is best conceptualized as a dynamic multifaceted construct, leading to a reconsideration of earlier findings and theories. Integrating these findings into a new theory of goal-directed cognition shows how rumination, much like a fugue or any musical composition, emerges from the orchestrated interplay between diverse psychological, neurological, and biological mechanisms. Thereby, just as fine-tuning one instrument does not guarantee an improved orchestral performance if other instruments are out of tune, addressing any single aspect of rumination in isolation is unlikely to significantly alter entrenched ruminative patterns or lead to better understanding rumination. Both studying rumination and intervening on rumination might require integrative, dynamic, and multivariate approaches that address its complex nature. Moreover, looking beyond our specific findings, I argued for broader changes in the scientific process within psychology. I advocate for considering the impact of our research methodologies on the hypotheses we can test and for the development of collaborative literature reviews and evolutive theory-building approaches to facilitate cumulative and iterative research efforts. Hence, as we reach the coda of this thesis, it is clear that the journey to fully comprehend rumination and its associations with executive control is far from over. Further research is needed to replicate the findings, expand and formalize the goal-directed cognition theory, continue using and improving intensive longitudinal methods, and refine our current scientific processes to enhance iteration and collaboration.

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Appendices

Appendix A.
Supplementary material from Chapter 7

Table S1. ESM Items in English and French

Item	Item FR	Translation EN	Anchors FR	Anchors EN
Perseverance	A quel point avez-vous passé du temps à penser à une ou plusieurs expériences émotionnelles ?	How much time did you spend thinking of one or more emotional experiences?	A aucun moment vs. Tout le temps	None / All the time
Criticism	A quel point vos pensées ont-elles été critiques envers vous-même ?	To what extent were your thoughts self-critical?	Pas du tout critiques vs. Extrêmement critiques	Not at all / Extremely
Negativity	A quel point vos pensées ont-elles été négatives ?	To what extent were your thoughts negative?	Pas du tout negatives vs. Extrêmement négatives	Not at all / Extremely
Brooding	Dans quelle mesure avez-vous pensé aux causes et aux conséquences d'expériences émotionnelles ?	How much did you think about the causes and consequences of emotional experiences?	Pas du tout vs. Tout à fait	Not at all / Absolutely
Replaying	A quel point avez-vous rejoué dans votre esprit des parties d'expériences émotionnelles que vous avez vécues ?	To what extent have you mentally replayed emotional experiences that you've had?	Pas du tout vs. Tout à fait	Not at all / Absolutely

Table S2. ESM Items tooltips in English and French

Item	Tooltip FR	Tooltip EN
Perseverance	Cette question se réfère à combien de temps vous étiez pris dans vos pensées, soit à penser à des émotions, à des problèmes, ou quelque chose qui vous est arrivé, plutôt que d'être absorbé par ce que vous faisiez.	This question refers to how much time you spent lost in your thoughts, thinking about emotions, problems, or something that happened to you, instead of being absorbed by the activity you were doing.
Criticism	On parle ici "d'auto-critique". Cela se réfère donc à des pensées envers vous-même lorsque : vous êtes mécontent de ce que vous faites ou comment vous agissez, mécontent de qui vous êtes, lorsque vous vous mettez des objectifs mais que vous vous critiquez si vous ne les avez pas encore atteints... A l'inverse, des pensées non critiques envers vous-mêmes sont des encouragements, de la compassion envers vous-même, un discours positif (p. ex., "je n'y suis pas arrivé maintenant mais je finirai par y arriver".)	This question refers to 'self-critical' thinking, meaning thoughts you have about yourself when: you're dissatisfied with what you're doing or how you're reacting, you're unhappy with who you are, or when you have goals in mind, but you criticize yourself that you haven't attained them yet... In contrast, thoughts about yourself that are not 'self-critical': these are encouragements, self-compassion, positive thinking (for ex.: "I wasn't able to do it now but I'll get there at some point").
Negativity	Se réfère au contenu de vos pensées : par exemple une situation négative, des événements négatifs, un mauvais souvenir, des sensations désagréables, des pensées décourageantes, des pensées par rapport à des émotions négatives (stress important, anxiété, colère)...	This refers to the content of your thoughts: for example, if you're thinking of a negative situation, negative events, bad memories, unpleasant sensations, discouraging thoughts, thoughts about negative emotions (intense stress, anxiety, anger), ...
Brooding	Si vous pensez aux causes ou aux conséquences d'une ou plusieurs expériences émotionnelles (positives ou négatives) actuelles ou passées. Quelques exemples : se demander ce qui a causé une dispute avec son/sa conjoint(e); réfléchir aux conséquences d'un appel de téléphone énervant; se demander pourquoi on a des difficultés à se concentrer; pourquoi vous vous sentez mal ou stressé(e); penser à	This refers to if you think of the causes or consequences of one or several emotional experiences (which could be positive or negative) that are either currently ongoing or in the past. A few examples: wondering what caused an argument with your partner; thinking about the consequences of a frustrating phone call; wondering why you have difficulty concentrating; trying to figure out why you feel bad or stressed; thinking about why you messed up a particular task; thinking about the causes and

	pourquoi vous avez raté une certaine tâche; penser aux causes et conséquences d'avoir raté un examen ou une interview pour un job; etc.	consequences of having failed an exam or a job interview; etc.
Replaying	Il s'agit de savoir si vous avez revécu en images certaines scènes d'un ou plusieurs expériences émotionnelles ou si vous avez rejoué l'événement en pensées, peu importe si c'était positif ou négatif.	This refers to whether you relived certain scenes from emotional experiences, or 'replayed' an event in your mind (regardless of whether it was a positive or negative experience).

Note. We used these tooltips (i.e., text boxes appearing on top of questions) instead of a study manual to provide readily available explanations of the ESM items to the participants. They were accessible at any time during the completion of the ESM survey: a simple touch or click on the questions would render the tooltip.

Description of pilots

We conducted two pilots that allowed us to test and improve the ESM items we had developed, and the ESM protocol created using *formr*. We tested two different frequency possibilities across these two pilot studies to arrive at one that was frequent enough for our analyses but not too burdensome for participants.

Eight participants answered the ESM items five times daily for three days in the first pilot. At each time point, we asked participants to think of a specific emotional event that happened since the last time point and answer the rumination items about that event. Based on qualitative feedback from the participants of this first pilot, answering five times a day was considered too burdensome, and thinking of a specific emotional event at each time point was considered too difficult. Hence, we modified the prompts and the frequency of the ESM survey and conducted a second pilot.

In this second pilot, seven new participants answered the ESM items four times a day (9 AM, 1 PM, 5 PM, and 9 PM). When answering, participants had to think about everything that had happened since they woke up (for the first survey) or since the previous questionnaire (for the following surveys). Moreover, we modified the introductory text of the ESM surveys to promote reflection when answering the ESM with the following instructions: "*There is no right or wrong answer. It is your experience and only your experience that we are interested in. Please take a few moments for yourself to reflect on the hours that have passed and answer these questions*". Because this second pilot was successful, we used these ESM items in a study with a community sample—the data used to validate the psychometric properties of the items in this paper.

Additional information about the ESM protocol

Summary of the briefing

The participants had an individual virtual briefing with the first author. During this briefing, the first author presented the study and the ESM items and sent a personalized study link to the participant. We asked them to open the link during the briefing session, enter their phone number and email address in the form and submit it. In this way, we verified that each participant could receive the alerts via text message. We told participants they would receive text messages with the link to the survey. As this link remained the same throughout the study, they could copy-paste it and answer from their computer each time they received a text message if they wished to do so.

Briefing canvas

First, we verified the inclusion and exclusion criteria with each participant at the start of the video call. Then, we reminded the participant of the study's goal and explained the ESM protocol in detail. For example, we mentioned the time the participant had to answer the ESM questionnaires (2 hours). We also specified that it was always better to try to respond immediately after receiving the alert to avoid forgetting to reply. Then, we opened a test version of the ESM questionnaire (through screen sharing), so the participant could familiarize themselves with the layout and the questions. We explained each item and made sure that the participant understood them. We filled in the questionnaire together once to have practice. We indicated that it is impossible to answer precisely in the middle of the 0 to 100 scale (to ensure they answer the survey). And we asked the participant to take their time to answer each question: "It is natural to take your time answering questions. Sometimes you might be able to answer them quickly; sometimes, it will take you more time. We are used to remembering what we have done in the last hour, but it can be harder to remember what we have thought about, or sometimes we remember a vague impression. Lastly, please don't answer randomly; sometimes you may forget to answer, or you might not have time to answer: in those cases, it is better not to answer rather than answer randomly or too quickly because it could distort the data."

After explaining the study, we explained how and when we sent the text messages. We specified that the participant could directly contact the first author through text message if they encountered an error or had a question, as this would allow the first author to respond promptly.

Next, we asked the participant whether he would agree to have a quick phone call in the next few days to ensure everything is going well and to answer any questions they might have. During this call, we asked the following questions: "Have you been able to fill in many of the diary entries?; How many do you think you have filled in?; Is there anything that's stopping you from filling them in?; Do you have any questions regarding the survey's items?; Would you like to ask me any questions?; Is there anything you are unsure about?"

In the next part of the briefing, we briefly explained the study's goal to the participants so they could understand the study's usefulness and that their efforts serve a bigger purpose. We presented the study this way: "In psychological sciences, studies often only use one measurement, which is thus a snapshot of people's symptoms, behaviors, and thoughts. Thus, this study is important because, in the psychological sciences, there is a severe lack of longitudinal studies with multiple measurement points. This study could, therefore, have interesting results and help us understand how our thoughts fluctuate over two weeks. In a second step, a better understanding of how our thoughts fluctuate and are related may allow us to improve existing therapies to make them even more effective. In addition, although your answers are anonymized, your contribution is appreciated as the more you answer, the more our statistical analyses will be reliable."

We then created a personalized anonymous formr.org link for the participant and sent it to them. We waited for them to fill in the first few demographics questions to ensure they enrolled without hiccups.

We finished the briefing with some important comments: "Before ending this call, let me summarize the main points. Please keep your usual daily routine but try to always have your phone with you. Try to answer the ESM surveys as soon as you receive the text message with the link; otherwise, it can be easy to forget. You will thus have to answer seven questions four times a day for 14 days. At the end of the 14 days, you will have four questionnaires to fill in. I will then contact you back for the next part of the study. Finally, do not hesitate to contact me by email or phone if you encounter a problem."

Additional features of the ESM procedure with Formr

We customized formr to improve user experience and participant compliance. First, instead of giving participants a study manual explaining the study and the items, we added "tooltips" to the questions: participants could tap on a question at any time, and a text box would appear with more information and explanation. Second, the page displayed a summary of the participant's progress for the day at the end of each ESM questionnaire. Participants saw how many questionnaires they answered today, how many they failed to respond to, and how many were left to answer. After the last daily ESM questionnaire, when they were waiting for the next day to start, participants saw a thank you message and their progress in the study (how many days had passed and how many days were left).

Moreover, suppose the participant answered less than two questionnaires that day. In that case, they saw the following text: "We notice you answered less than two questionnaires today: do not hesitate to contact me (email of the researcher) if there are any difficulties with the study." If the participant had a completion rate above 70% for the day, then a text showed up saying, "Today, you had a completion rate of xx%! This is great; thank you for taking this research seriously". Third, we added precisely timed encouragement texts within the surveys to increase compliance (see *Table S3*). For example, at the end of the 8th day, participants would see this text upon completing the ESM survey: "*This is remarkable. You have completed more than half of the study! Your experience and your involvement in this research directly enhance the quality of this research. Thank you for your commitment!*". Participants saw these messages on the webpage at the end of the day to motivate them to continue answering well and give them a sense of progress. Fourth, the default answer on each ESM question was 50. Participants had to enter any other value for their response to be valid. Only when they answered all the questions would the submit button appear. We did this to ensure participants would not forget or avoid answering a question before submitting the ESM survey. Lastly, we also customized the visual appearance of the formr surveys (we provide the CSS code we used in the formr RUN file on the OSF repository).

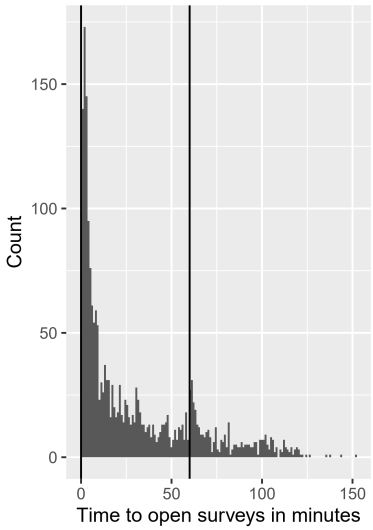
ESM survey timeout details

Once the participant had opened the questionnaire (i.e., the participant opened the ESM survey in a browser), it would time out and become unavailable if participants had not submitted their answers within 70 minutes or would timeout in 10 minutes after the 2-hour access window (e.g., in case the participant forgot or failed to submit his answers after opening the survey).

Table S3. Timed Encouragement Texts

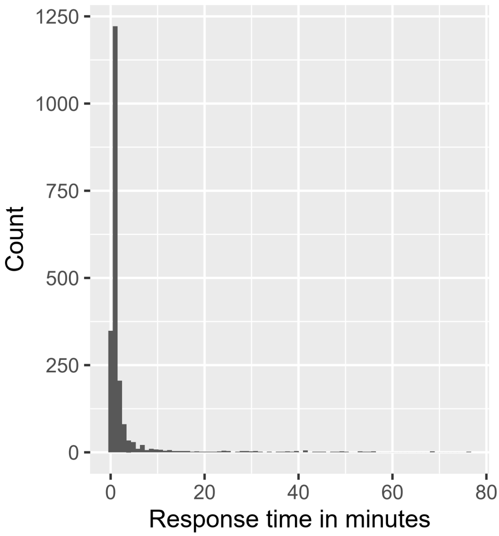
Day	Text
1st	"Thank you for your participation! Please do not hesitate to let us know of any difficulties you may encounter in completing the questionnaires or participating in this study: researcher's email"
4th	"Already four days! We want to thank you and encourage you to continue. As simple as it may seem, each answer you provide improves the quality of this study, helps us better understand our thoughts in our daily lives, and, above all, contributes to the advancement of psychological research. Thank you for your involvement throughout these four days. Please do not hesitate to send us your questions or concerns about the questionnaires (email). This study is unique, and so is your participation."
8th	"This is remarkable. You have completed more than half of the study! Your experience and involvement in this research directly enhance the quality of this research. Thank you for being so committed!"
11th	"Only three days left; it's the final stretch! Every answer matters and allows us to make our statistical analysis more reliable."
13th	"The end of the study is near; only one day left!"

Figure S1. Time to open the ESM survey in minutes



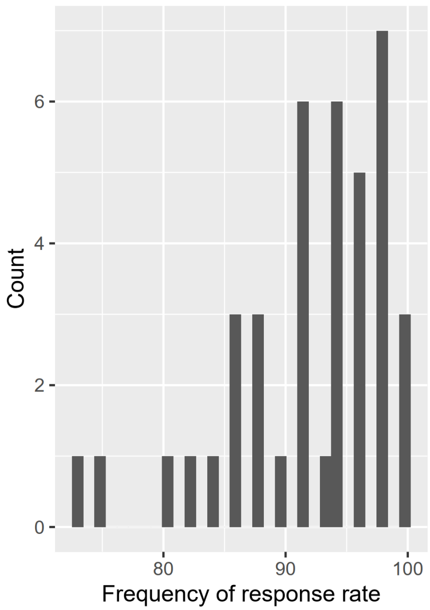
Note. The first vertical line represents the moment an alert was sent by text message. The second vertical line is when a reminder was sent out (60 minutes after the first alert). The y axis represents the number of observations.

Figure S2. Response time to complete and submit answers to the ESM items



Note. The outliers are either because some participants left the web page open and only submitted their answers after realizing they forgot to press the "submit" button or because some participants started answering the survey but only finished answering later.

Figure S3. Frequency of response rate



Note. The frequency of participants' compliance rate (in %)

ESM feedback

After the study, participants were asked by email to answer an optional survey (on Qualtrics) containing questions about the ESM items and how they experienced the study. In a series of questions using Likert scales, we asked participants to what extent they understood the questions (i.e., whether they were clear enough), to what extent they felt each question could capture the daily fluctuations it aimed to measure, and whether they could easily translate their everyday experience when answering the question (i.e., whether the continuous scale and the survey were easy to use and to express nuances). Participants could add additional comments for each item to nuance their quantitative answers. We also asked participants whether they used their phone, computer, or both to answer the questionnaires. Next, we asked participants a series of open-ended questions to get a wide range of qualitative feedback. And finally, we asked participants whether they would recommend the study to somebody else, whether they experienced COVID-related anxiety during the study, and to what extent this anxiety had influenced their answers. As this feedback questionnaire was optional, not all participants answered it; 5 participants dropped out. In the results section, we summarize the qualitative and quantitative feedback from the participants (n = 35) regarding their experience during the ESM study.

We provide descriptive statistics of the quantitative answers of participants' feedback in *Table S4*. Overall, participants' feedback indicated that the items sufficiently captured daily fluctuations (except brooding and self-criticism scoring the lowest) and that participants could understand them and answer them well enough (brooding scored the lowest, with a median of 3/7). This suggests that the briefing should perhaps include a more thorough explanation of brooding. Next, regarding the open-ended questions (see section "Qualitative assessment of the ESM items" for more details), the answers indicate that most participants considered that the study was not burdensome and that their participation did not hinder their family or work life (although it should be noted that all but one participant were students). Interestingly, as mentioned in the results section, some participants highlighted that 9 AM might be too early (as nothing much had happened yet) and that 9 PM might be too late to answer ESM surveys. However, one participant said they also ruminated at night and that the ESM surveys did not consider this—a few participants reported similar observations during informal exchanges with the first author. Indeed, our ESM protocol did not cover nighttime rumination because of how we set up the questionnaires. Moreover, 94% of the participants exclusively used their phones to answer the surveys; the others used a computer from time to time (by copy-pasting the link and bookmarking it in their web browser). Lastly, participants were neutral about recommending this study to other participants (*median* = 4) and had only a little COVID-related anxiety (*median* = 3), which did not have a significant impact on their answers during the study (*median* = 2).

Table S4. Descriptive statistics of participants' answers to quantitative feedback questions

Question	***M***	***SD***	***Median***
ESM items			
Ease of understanding			
Perseveration	3.66	1.11	4
Negativity	3.54	0.82	4
Criticism	4.09	1.07	4
Brooding	3.34	1.21	3
Replaying	3.60	1.14	4
Ease of answering the question & translating their experience			
Perseveration	3.94	1.28	4
Negativity	3.83	1.07	4
Criticism	4.43	1.27	5
Brooding	2.89	1.16	3
Replaying	3.29	1.30	3
Adequately capturing daily fluctuations			
Perseveration	4.06	1.37	4
Negativity	4.91	1.31	5
Criticism	3.43	1.12	3
Brooding	2.91	1.12	3
Replaying	4.40	1.31	5
Additional questions			
Would you recommend this study to somebody else?	3.66	1.16	4
Did you feel covid-related anxiety or a bad mood (COVID-related) during this study?	2.77	1.57	3
To which extent did this anxiety or bad mood influence your answers?	2.80	1.86	2

Note. Questions were rated on a Likert scale from 1 (not at all) to 7 (absolutely).

Qualitative Assessment of the ESM items (open-ended questions)

Perseveration

One participant said that as they went through various emotional phases during the four last hours, they tended to answer according to the last 30 minutes. For another participant, it was hard to know whether stress had to be part of this question as they did not see it as an emotional experience because they were constantly stressed about their exams. Finally, one participant sometimes did not know whether they had to refer to emotional experiences experienced during the day or emotional experiences they thought of during the day (i.e., it is both).

Negativity

Some participants had trouble evaluating to which extent their thoughts were negative.

Self-criticism

Some participants highlighted that their answers for negativity and self-criticism were similar. One participant said self-criticism could be positive and negative (although we specifically asked to answer regarding negative unconstructive self-criticism).

Brooding

Two participants found that answering this question took more time.

Replaying

For a few participants, this question was too similar to the question about perseveration. However, one specified that reading the explanation provided in the tooltip helped answer and distinguish the questions.

Qualitative Assessment of the overall experience of the ESM study (open-ended questions)

Did you experience any technical difficulties in participating in this study, and if so, what were they?

A majority of participants did not encounter any technical difficulties. Those who did is because they did not have access to their phone at some moments.

Did you experience any negative emotions while participating in this study, and if so, which ones?

Most participants did not experience negative emotions. Some found that the study forced them to think about unpleasant experiences and was strongly focused on negative questions. Some thought the study was a burden that added to the stress of exams. One participant said it led to negative thoughts that were not present at first, and one said they realized they had too many negative thoughts.

Were you hindered, even partially, by the daily burden this questionnaire imposes?

Some participants thought of the study as homework to do and thus saw it as an inconvenient burden when they were busy, but overall, most participants answered no.

Has it been difficult to combine family/work life with participation in this study?

Other than a few cases in which they forgot or couldn't answer the questions, participants said that it did not hinder their family/work life.

To what extent did you consider your daily participation in this study a burden?

Some participants found it annoying when a reminder or an alert arrived during a calm or important moment. Some did not see it as a burden, although they always had to keep it in mind. A few participants found that four times a day was too much.

Did you feel that your answer in your head was perfectly captured when you answered using the slider? If not, why not?

About half of the participants found the slider convenient for answering the questions. Other participants said they would have preferred a shorter scale (e.g., 1 to 5 or 1 to 10) as they considered the scale to be too precise.

Do you have any comments about the general interface of the questionnaire? Is the tool easy to use?

Many participants here highlighted the ease of use and that they liked the interface of the questionnaire.

Did you find the system of sending the link to the questionnaire (the SMS) annoying?"

All participants answered no to this question.

Would you have preferred to be sent an email rather than a text message?

All participants but one said they preferred text messages. The one participant that preferred receiving emails said so because it would have allowed them to not keep their phone next to them while working.

What did you think of the times the surveys were sent (9 AM, 1 PM, 5 PM, and 9 PM)? Would you recommend different times? If so, why?

Some participants highlighted that 9 AM (as they did not have the time yet to think about many things) was a bit early and that 9 PM could be a bit late sometimes.

To answer, you had to think back to the hours that had passed since you woke up or since the previous questionnaire. (a) Did you find this exercise difficult given the questions? (b) Do you have any examples of questions where this exercise was much more complicated to complete?

Only a few participants said it was hard to remember what happened during the hours between the surveys or that it required a lot of introspection. Some also noted that the morning questionnaire was harder to answer if they woke up around nine or later as nothing much had happened yet.

Do you have other comments and/or suggestions about this study or the questionnaire?

One participant suggested to consider the hours during the night as well because sometimes they ruminated the most during the night.

What did you like about participating in this study?

Overall, participants liked the introspection, that is, how the study made them more conscious of their thoughts and emotions over several days.

How to use this ESM tool

The detailed instructions and the code to use this ESM tool or replicate this study can be found on OSF: https://osf.io/dngyk/.

See the document titled “ESM-RUM_Formr_Instructions.docx”.

Appendix B.
Supplementary material from Chapter 8

1. Inclusion criteria

The study which participants were recruited for consisted of two phases: an ESM phase and a second experimental phase consisting of neuromodulation using transcranial Direct Current Stimulation. Therefore, to be included in the larger study, participants had to: be between 18 and 60 years old, be exclusively right-handed, speak French, have a smartphone (to be able to receive text messages and answer the questionnaire on a web browser on the phone), not be pregnant, not have gone through neurosurgical procedures, not have any neurological issues, not present signs of epilepsy (or antecedents of epilepsy in the family) nor have chronic migraine, not have metallic implants in the brain or face, not have sensitive skin, and not have a ventricular or cerebral drain.

2. Sample Size

We considered previous research using a similar study design and the same type of statistical analyses (i.e., a multilevel vector autoregressive model) to determine the number of participants needed. Our study comprised 56 measure points (4 times a day for 14 days) of 7 items. Therefore, we aimed to recruit 40 participants with an overall completion rate of at least 70% to ensure similar statistical power as previously published studies (e.g., Curtiss et al., 2019; Ellison et al., 2020; Faelens et al., 2021; Greene et al., 2018). We planned to remove participants with less than one-third of the assessments completed (Delespaul, 1995) or less than 20 assessments in line with previous ESM studies (Greene et al., 2018; Myin-Germeys et al., 2001; Palmier-Claus et al., 2011) but no participants met these exclusion criteria.

3. Trait measures

This study used three self-report trait questionnaires: the Beck Depression Inventory (BDI-II; Beck et al., 1996), the Generalized Anxiety Disorder scale (GAD-7; Spitzer et al., 2006), and the Ruminative Response Scale (RRS-10; Treynor et al., 2003). The BDI-II assesses symptoms of depression, the GAD-7 assesses generalized anxiety disorder symptoms, and the RRS measures the tendency to ruminate. We only use the brooding and reflection subscales, each made of five items of the 22 items of the RRS (RRS; Treynor et al., 2003). We used the French versions of these scales. We computed the total scores for each questionnaire, with higher scores indicating worse symptomatology (see Table S1 for descriptive statistics of the trait questionnaires). The participants answered the questionnaires at the end of the ESM procedure, reflecting their experience over the prior two weeks.

Table S1. Descriptive Statistics of Trait Questionnaires

Questionnaire	*n*	*Mean*	*SD*	min	max	Range	*α*
GAD-7	40	6.25	3.81	0	16	0–21	0.76
BDI-II	40	11.8	6.90	1	34	0–63	0.82
RRS Brooding	40	5.9	3.18	1	15	0–15	0.73
RRS Reflection	40	4.48	2.94	0	15	0–15	0.71
RRS-10	40	10.38	5.09	1	22	0–30	0.77

Note. GAD-7 = general anxiety symptoms; BDI-II = depression symptoms; Brooding = brooding subscale of the RRS; Reflection = reflection subscale of the RRS; RRS-10 = comprises the brooding and the reflection subscales.

4. Items in English and in French

Table S2. Items in English and in French

Item	FR	EN	Anchors FR	Anchors EN
Attention Control	Lorsque j'ai voulu volontairement me concentrer sur quelque chose, j’ai été capable d’ignorer des distracteurs environnants (bruit, tentations, notifications, distracteurs visuels...).	When I wanted to deliberately concentrate on something, I was capable of ignoring environmental distractions (noise, notifications, visual distractors, ...)	A aucun moment vs. Tout le temps	Not at all / all the time
Perseveration	A quel point avez-vous passé du temps à penser à une ou plusieurs expériences émotionnelles ?	How much time did you spend thinking of one or more emotional experiences?	A aucun moment vs. Tout le temps	None / All the time
Criticism	A quel point vos pensées ont-elles été critiques envers vous-même ?	To what extent were your thoughts self-critical?	Pas du tout critiques vs. Extrêmement critiques	Not at all / Extremely

Item	FR	EN	Anchors FR	Anchors EN
Negativity	A quel point vos pensées ont-elles été négatives ?	To what extent were your thoughts negative?	Pas du tout negatives vs. Extrêmement négatives	Not at all / Extremely
Brooding	Dans quelle mesure avez-vous pensé aux causes et aux conséquences d'expériences émotionnelles ?	How much did you think about the causes and consequences of emotional experiences?	Pas du tout vs. Tout à fait	Not at all / Absolutely
Replaying	A quel point avez-vous rejoué dans votre esprit des parties d'expériences émotionnelles que vous avez vécues ?	To what extend have you mentally replayed emotional experiences that you've had?	Pas du tout vs. Tout à fait	Not at all / Absolutely

Note. Details about item development and their psychometric assessment can be found in Hoebeke et al. (2022).

Table S3. Tooltips provided with each item

Variable	Tooltip FR	Tooltip EN
Attentional Control	Cette question se réfère au fait que parfois on peut facilement être absorbé dans une activité sans aucun souci tandis qu'à d'autres moments on va avoir du mal à se concentrer, soit parce qu'on est trop dans nos pensées, soit parce qu'on est distrait par des notifications de téléphone, soit parce que du bruit nous dérange...	This question refers to how sometimes we can easily be absorbed in an activity, while other times we'll have difficulty concentrating, either because we're too lost in our thoughts we're distracted by phone notifications, by noise, ...
Perseverance	Cette question se réfère à combien de temps vous étiez pris dans vos pensées, soit à penser à des émotions, à des problèmes, ou quelque chose qui vous est arrivé, plutôt que d'être absorbé par ce que vous faisiez.	This question refers to how much time you spent lost in your thoughts, either thinking about emotions, problems, or something that happened to you, instead of being absorbed by the activity you were doing
Criticism	On parle ici "d'auto-critique". Cela se réfère donc à des pensées envers vous-même lorsque : vous êtes mécontent de ce que vous faites ou comment vous agissez, mécontent de qui vous êtes, lorsque vous vous mettez des objectifs mais que vous vous critiquez si vous ne les atteignez pas... A l'inverse, des pensées non critiques envers vous-mêmes sont des encouragements, de la compassion envers vous-même, un discours positif (p. ex., "je n'y suis pas arrivé maintenant mais je finirai par y arriver".)	This question refers to 'self-critical' thinking, meaning thoughts you have about yourself when: you're dissatisfied with what you're doing or how you're reacting, you're unhappy with who you are, or when you have goals in mind, but you criticize yourself that you haven't attained them yet... In contrast, thoughts about yourself that are not 'self-critical': these are encouragements, self-compassion, positive thinking (for ex.: "I wasn't able to do it now, but I'll get there at some point")
Negativity	Se réfère au contenu de vos pensées : par exemple une situation négative, des événements négatifs, un mauvais souvenir, des sensations désagréables, des pensées décourageantes, des pensées par rapport à des émotions négatives (stress important, anxiété, colère)...	This refers to the content of your thoughts: for example, if you're thinking of a negative situation, negative events, bad memories, unpleasant sensations, discouraging thoughts, thoughts about negative emotions (intense stress, anxiety, anger), ...
Brooding	Si vous pensez aux causes ou aux conséquences d'une ou plusieurs	This refers to if you think of the causes or consequences of one or several

	expériences émotionnelles (positives ou négatives) actuelles ou passées. Quelques exemples : se demander ce qui a causé une dispute avec son/sa conjoint(e); réfléchir aux conséquences d'un appel de téléphone énervant; se demander pourquoi on a des difficultés à se concentrer; pourquoi vous vous sentez mal ou stressé(e); penser à pourquoi vous avez raté une certaine tâche; penser aux causes et conséquences d'avoir raté un examen ou une interview pour un job; etc.	emotional experiences (which could be positive or negative) that are either currently ongoing or in the past. A few examples: wondering what caused an argument with your partner; thinking about the consequences of a frustrating phone call; wondering why you have difficulty concentrating; trying to figure out why you feel bad or stressed; thinking about why you messed up a particular task; thinking about the causes and consequences of having failed an exam or a job interview; etc.
Replaying	Si vous avez revécu en images certaines scènes de l'expérience émotionnelle, vous avez rejoué l'événement en pensées, peu importe si c'était positif ou négatif.	This refers to whether you relived certain scenes from emotional experiences, or 'replayed' an event in your mind (regardless of whether it was a positive or negative experience)

Note. Participants could click on each question of the ESM survey at any time and see these tooltips.

5. Network analysis

We computed a contemporaneous, a temporal, and a between-subjects network. The *between-subject* network uses the person-level mean (i.e., an average of all the ESM observations per participant) of each variable controlling for all other variables and contemporaneous and temporal effects. The *contemporaneous* network investigates concurrent relations between nodes by controlling for temporal effects and all other variables at the same time point. To compute the contemporaneous network, the residuals of the mlVAR model for each variable are regressed on all the residuals for all other variables from the same time point. The *temporal* network uses within-subject centered lagged variables as within-subjects level predictors. The temporal network represents the temporal associations from one time point to the next, controlling for all other associations. Following Epskamp (2018), nights were handled by adding a row of missing values between consecutive days (the mlVAR package performs this). In this way, the first measurement of the day was not regressed on the last measurement of the previous day. All pairs of lagged and current variables containing missing responses were removed.

Appendix C.
Supplementary material from Chapter 9

1. Results from the Transfer Entropy Analysis with varying max_lag parameters

Although the cut-off for the maximum number of lags to consider was set to 19, equivalent to five days of data, we also computed the analyses with one-, two-, three-, and four-days' worth of data. The uncovered associations are sparser the more lags are considered. More worryingly, some associations are reversed: when the maximum lag is set to 15, perseveration predicts negativity, whereas when it is set to 11, negativity predicts perseveration. Several aspects remain the same throughout the different analyses however: (1) attention control always has the lowest omnibus transfer entropy value, followed by self-criticism and negativity, whereas perseveration, replaying, and brooding have high transfer entropy; (2) brooding, replaying, and perseveration are consistently associated, seemingly forming a cluster; (3) all past lags are significant for negativity and self-criticism, similar to the results from the analysis with maximum lag set to 19.

Figure S1. Results with max_lag set to 3

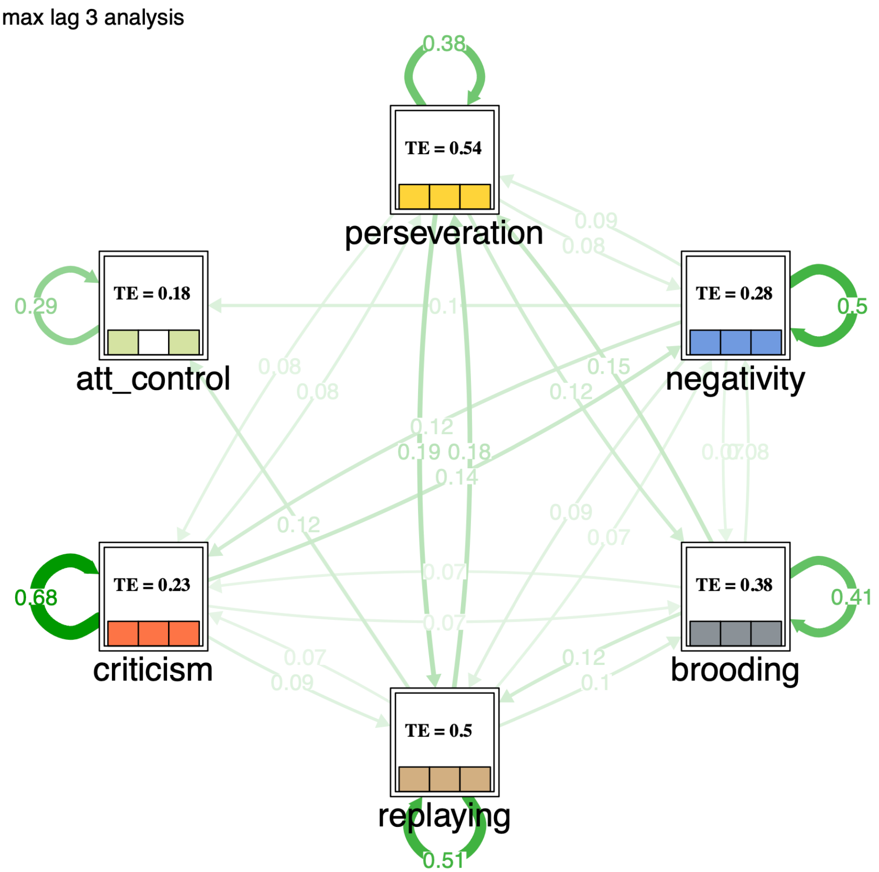


Figure S2. Results with max_lag set to 7

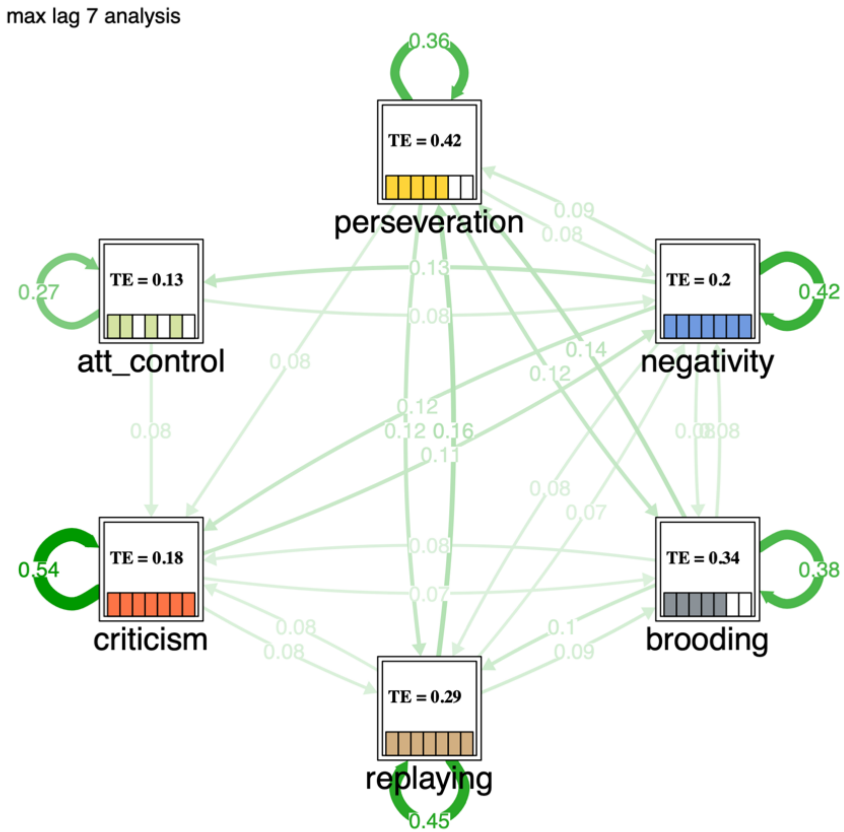


Figure S3. Results with max_lag set to 11

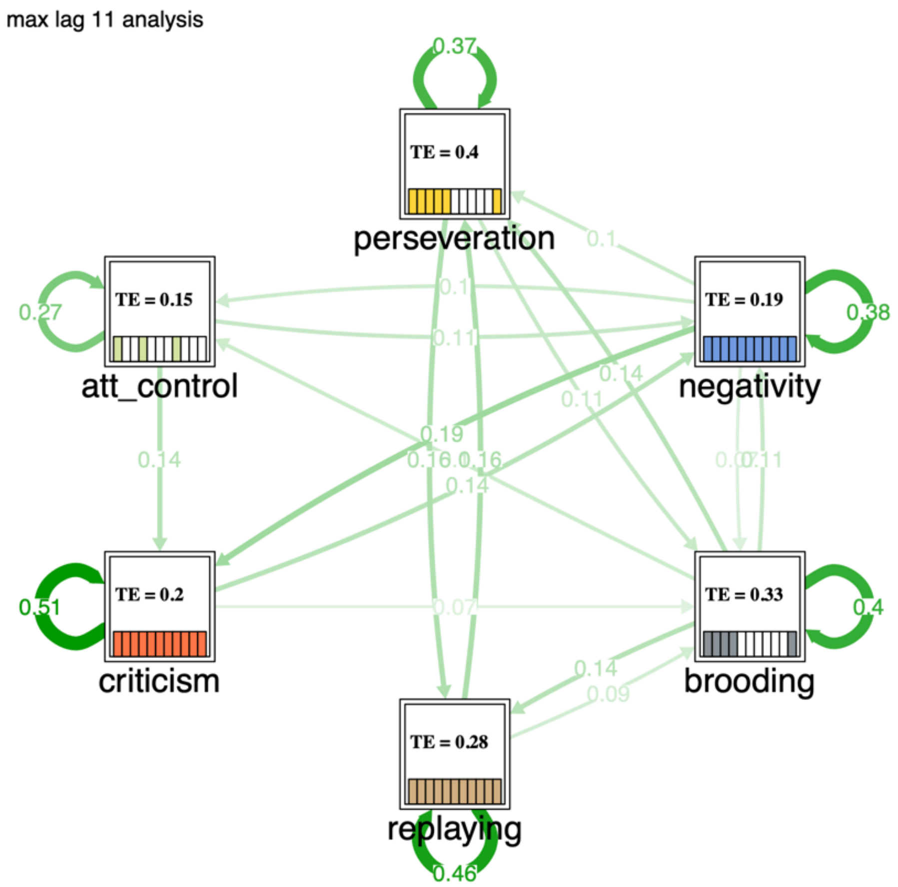
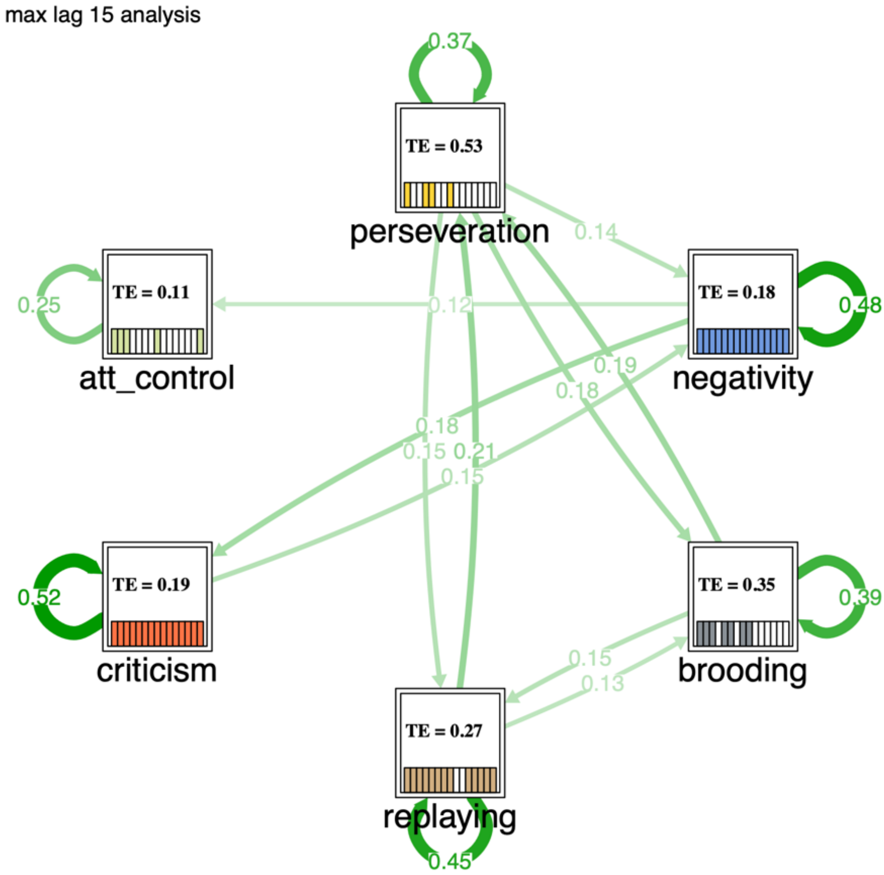
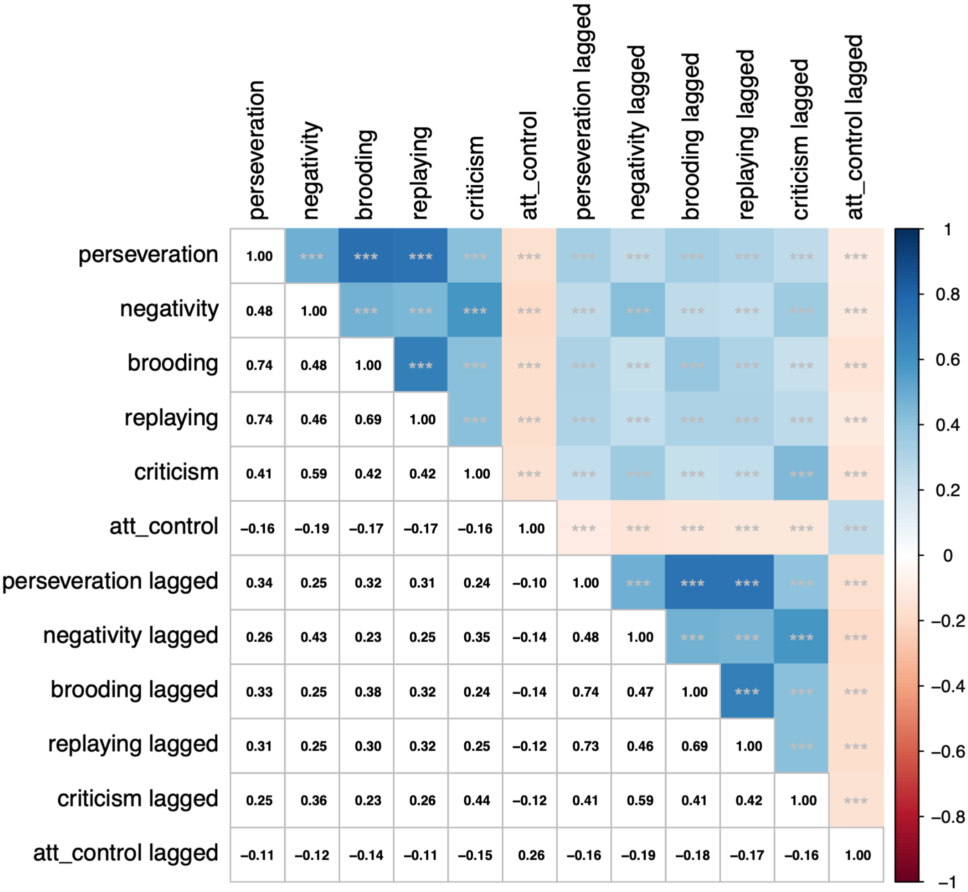


Figure S4. Results with max_lag set to 15



2. Correlation Matrix

Figure S5. Correlation matrix of ESM variables and their lagged values



Note. The correlations with the “lagged” variables correspond to the correlation with that variable at the previous time point.

Appendix D.
Supplementary material from Chapter 10

Descriptive statistics

Table S1. Descriptive Statistics of Trait Measures and ESM Measures

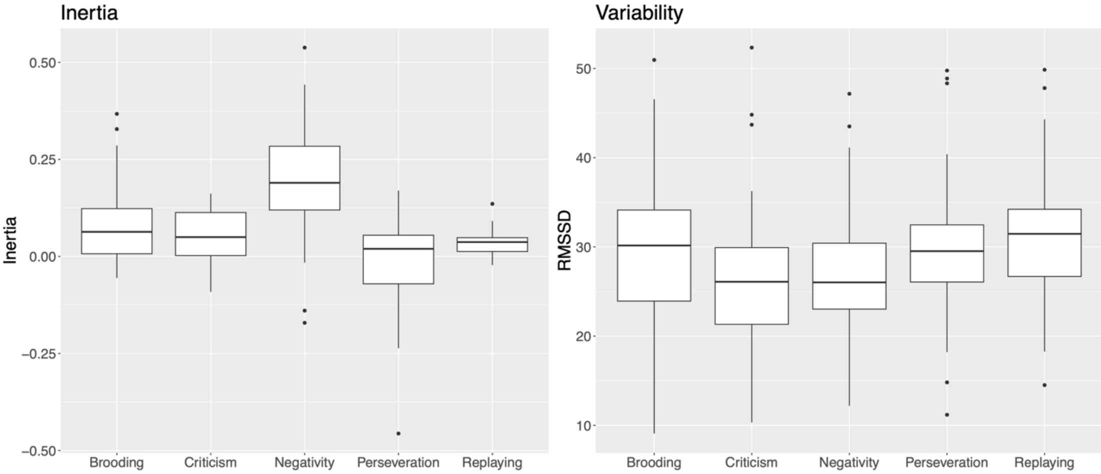
	mean	*SD*	*median*	*min*	*max*
GAD-7	6.33	3.83	7.00	0.00	16.00
BDI-II	12.44	7.12	12.00	1.00	35.00
RRS10	10.41	5.15	11.00	1.00	22.00
Perseveration PL mean	37.41	13.97	37.35	6.06	71.15
Negativity PL mean	28.44	13.02	26.45	3.55	62.49
Brooding PL mean	33.93	14.31	30.96	5.72	67.49
Replaying PL mean	34.96	13.79	35.98	5.74	66.85
Criticism PL mean	30.00	15.12	25.24	4.18	57.93
Perseveration inertia	-0.02	0.12	0.00	-0.47	0.17
Negativity inertia	0.19	0.13	0.19	-0.14	0.53
Brooding inertia	0.09	0.11	0.07	-0.05	0.42
Replaying inertia	0.03	0.03	0.03	-0.03	0.13
Criticism inertia	0.05	0.07	0.06	-0.13	0.18
Perseveration RMSSD	29.99	8.47	29.52	11.18	49.77
Negativity RMSSD	26.72	7.73	26.02	12.18	47.17
Brooding RMSSD	29.03	8.49	30.16	9.08	50.96
Replaying RMSSD	31.07	7.76	31.46	14.51	49.86
Criticism RMSSD	25.94	8.75	26.09	10.32	52.35
Perseveration PL SD	23.40	5.29	23.13	8.73	35.27
Negativity PL SD	22.19	5.33	22.63	8.23	33.18
Brooding PL SD	23.09	6.05	23.27	7.52	36.05
Replaying PL SD	24.01	4.68	24.36	15.24	36.25
Criticism PL SD	20.42	5.90	21.18	8.50	33.71

Note. PL mean = person-level/within-person mean; PL SD = person-level/within-person SD; BDI-II = Beck Depression Inventory; GAD-7 = Generalized Anxiety Disorder scale; RRS-10 = Ruminative Response Scale with 10 items.

Boxplot of inertia and moment-to-moment variability

Figure S1 shows boxplots of inertia and variability. Negativity has the highest inertia, while perseveration has the lowest inertia, with several participants exhibiting negative perseveration inertia. High negative inertia indicates a likely lower value at the next time point following a high value for a variable, and vice versa. In terms of variability, criticism and negativity show the lowest.

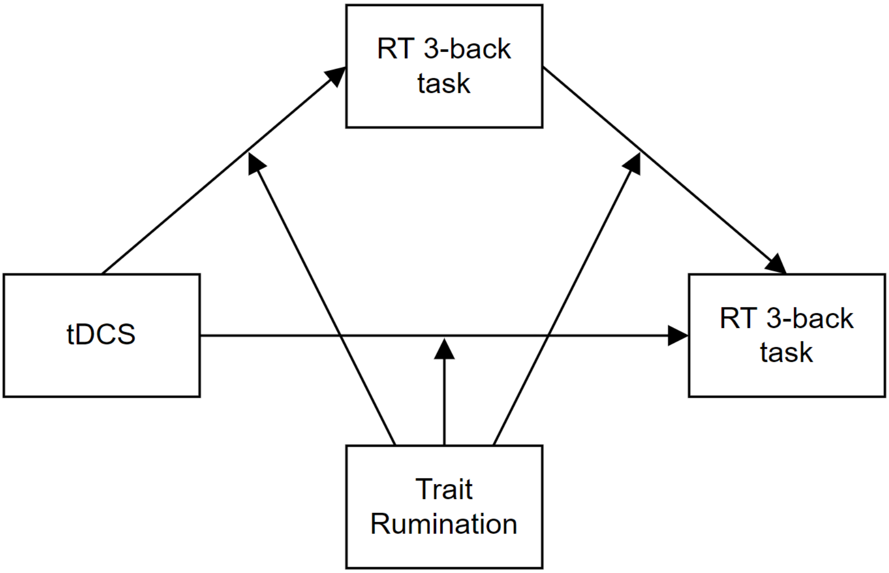
Figure S1. Boxplot of Inertia and Moment-to-moment Variability (RMSSD) of the ESM items



Appendix E.
Supplementary material from Chapter 12

1. Moderated Mediation

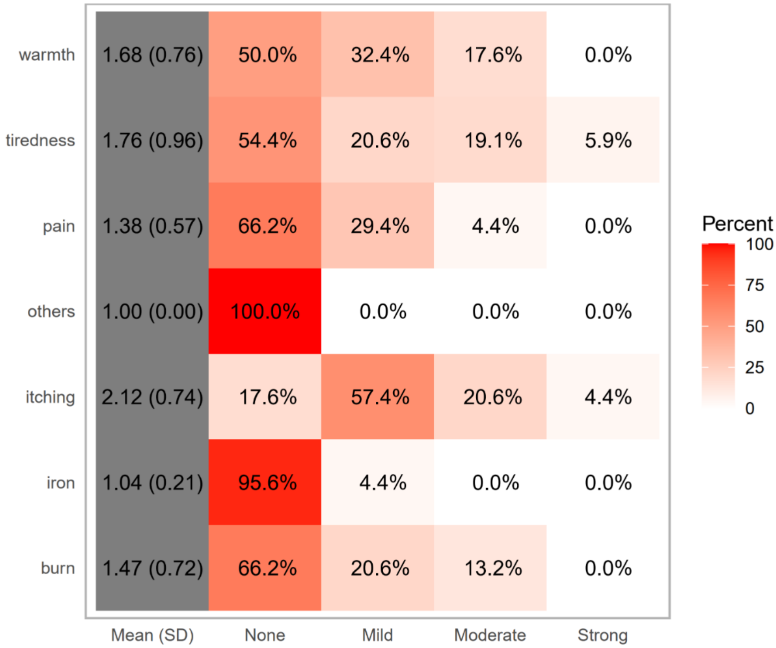
Figure S1



2. Sensations felt during tDCS stimulation

We used the questionnaires of Antal et al. (2017) to assess the sensations participants felt during the tDCS stimulation in both sessions. We asked the participants to indicate for each session the extent to which they felt the following: warmth, tiredness, pain, itching, iron/metallic taste, burning sensation, or other sensations. The results are shown in Figure S1. Additionally, we computed a t-test score to analyze whether the intensity of sensations was different for the anodal stimulation compared to the sham stimulation: the intensity of sensations was not significantly different for anodal stimulation compared to sham stimulation ($t(33) = 1.27$, $p = 0.21$).

Figure S2. Sensations felt during the tDCS stimulation



3. Stress manipulation check

We conducted paired t-tests between the stress scores before and after the tDCS and after the resting period. There was only a significant difference between pre-tDCS stress and stress during the stressor (5.9% increase in stress, t(38) = -2.72, p = 0.004), and the difference between stress after tDCS and stress during the task (3.4% increase in stress, t(38) = -1.41, p = 0.082). There were no significant differences between stress before and after tDCS (2.4% increase in stress, t(38) = -1.21, p = 0.116). Although the increase in stress after the stressor is significant compared to the stress before the tDCS, it represents only a 5.9% increase in stress.

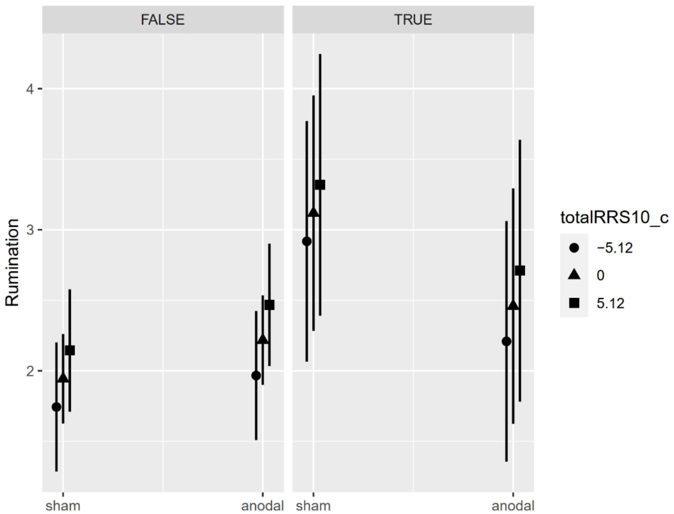
4. Blinding

We found a main effect of blinding for the total rumination score (and for the brooding feature of rumination), indicating that participants who guessed the condition correctly had significantly higher rumination and brooding than those that did not. There was also a significant interaction effect between condition and guessing the blinding on the self-criticism features of state rumination (see Table S1 in the Supplemental Material). This means that the two groups of participants (those that guessed correctly versus those who did not) had significantly different impact of tDCS on self-critical thoughts. While participants who did not correctly guess the stimulation types tended to exhibit slightly more self-critical thoughts in the anodal condition, those who correctly guessed the stimulation types had more rumination in the sham condition and less self-critical thoughts in the anodal condition. The interaction effect was not significant for total state rumination but tended in the same direction (B = -.23, p = .127, see Figure S3).

These results suggest that correctly guessing the blinding influenced participants' rumination and even influenced the effect of tDCS in the case of self-criticism. Therefore, we only reported the results of the analyzes without these five participants.

Importantly, these results indicate a potential placebo effect: the effect of tDCS on the state rumination of participants who guessed correctly aligned with our hypotheses, unlike those who did not guess correctly (see Table S1 and Figure S3). Since tDCS effects can be influenced by participant expectations regardless of blinding type (i.e., single vs. double blind, Rabipour et al., 2018), participants with optimistic expectations regarding tDCS might have been primed to benefit more from real stimulation compared to sham stimulation. Alternatively, correct guesses of being in a sham condition might have nullified the placebo effect, while a placebo effect might have been seen in the anodal condition (see Braga et al., 2021, for a narrative review of the role of expectation and beliefs on the effects of non-invasive brain stimulation).

Figure S3. Effect of tDCS on Total State Rumination by Blinding and Trait Rumination



Note. Plot of the marginal effects of tDCS condition on total state rumination by blinding (i.e., TRUE vs. FALSE) and centered trait rumination (i.e., totalRRS10_c).

Table S1. Linear Mixed models of total state rumination and features of rumination with the full sample

	Total State Rumination				Negativity				Brooding				Replaying				Self-Criticism				Perseveration			
Predictors	*B*	*SE*	*t(35)*	*p*	*B*	*SE*	*t(35)*	*p*	*B*	*SE*	*t(35)*	*p*	*B*	*SE*	*t(35)*	*p*	*B*	*SE*	*t(35)*	*p*	*B*	*SE*	*t(70)*	*p*
(Intercept)	2.43	0.17	14.56	**<0.001**	0.35	0.05	7.03	**<0.001**	0.48	0.04	11.23	**<0.001**	0.55	0.05	10.68	**<0.001**	0.47	0.05	9.53	**<0.001**	0.59	0.04	13.95	**<0.001**
Stimulation order	0.13	0.12	1.14	0.264	0.01	0.03	0.34	0.739	0	0.03	0.05	0.958	0.03	0.04	0.88	0.383	0.03	0.03	0.95	0.346	0.05	0.03	1.88	0.065
Session	0.38	0.1	3.67	**0.001**	0.03	0.02	1.31	0.199	0.07	0.03	2.69	**0.011**	0.1	0.03	3.89	**<0.001**	0.07	0.02	2.7	**0.011**	0.11	0.03	3.7	**<0.001**
Guessed	-0.35	0.17	-2.11	**0.042**	-0.04	0.05	-0.85	0.4	-0.09	0.04	-2.21	**0.034**	-0.09	0.05	-1.66	0.105	-0.06	0.05	-1.21	0.235	-0.07	0.04	-1.69	0.095
Condition	0.1	0.15	0.65	0.52	0.01	0.03	0.29	0.77	0.04	0.04	0.93	0.36	0	0.04	-0.05	0.962	0.07	0.03	1.88	0.068	-0.01	0.04	-0.32	0.751
RRS-10	0.04	0.02	1.92	0.063	0.01	0.01	1.93	0.062	0.01	0.01	2.49	**0.018**	0	0.01	0.53	0.599	0.01	0.01	1.57	0.125	0	0.01	0.3	0.764
Condition × Guessed	-0.23	0.15	-1.57	0.127	-0.05	0.03	-1.64	0.109	-0.06	0.04	-1.58	0.122	-0.02	0.04	-0.59	0.562	-0.09	0.04	-2.68	**0.011**	0	0.04	-0.08	0.939
Condition × RRS-10	0	0.02	-0.24	0.81	0	0	-0.25	0.805	0	0.01	-0.84	0.407	0	0.01	0.02	0.985	0	0	0.84	0.408	0	0.01	-0.6	0.554
Marginal R^2 / Conditional R^2	0.249 / 0.338				0.114 / 0.521				0.234 / 0.291				0.182 / 0.418				0.164 / 0.438				0.236 / NA			

Note. N = 39; Observations = 78; Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first); RRS-10 = trait rumination (mean-centered); Guessed = whether participants correctly guessed the stimulation type of both sessions.
[a]The model had a singular fit; random effects were estimated as being null.

5. Effect of tDCS on 1-back and 2-back tasks

Table S2. Effect of tDCS on 1-back and 2-back tasks

	d' 1-back				*RT* 1-back (log transformed)				*d'* 2-back				*RT* 2-back (log transformed)			
Predictors	*B*	*SE*	*t(31)*	*p*	*B*	*SE*	*t(27)*	*p*	*B*	*SE*	*t(27)*	*p*	*B*	*SE*	*t(28)*	*p*
(Intercept)	3.89	0.07	53.96	**<0.001**	2.71	0.01	289.01	**<0.001**	3.58	0.08	46.34	**<0.001**	2.81	0.01	250.26	**<0.001**
Stimulation order	-0.04	0.08	-0.47	0.639	0.03	0.01	2.76	**0.01**	-0.14	0.08	-1.65	0.111	0.02	0.01	1.62	0.116
Session	-0.1	0.05	-1.83	0.077	0.03	0.01	5.29	**<0.001**	-0.07	0.06	-1.14	0.266	0.06	0.01	9.89	**<0.001**
Condition	0.04	0.05	0.81	0.425	0	0.01	0.64	0.527	0.04	0.05	0.66	0.514	0	0.01	-0.25	0.807
RRS-10	-0.03	0.01	-2.04	**0.05**	0	0	1.08	0.292	-0.04	0.02	-2.85	**0.008**	0	0	-0.05	0.964
Condition × RRS-10	-0.01	0.01	-1.39	0.173	0	0	0.39	0.702	-0.02	0.01	-1.46	0.155	0	0	0.56	0.581
N	34 ID				30 ID				30 ID				31 ID			
Observations	68				60				60				62			
Marginal R^2 / Conditional R^2	0.114 / 0.413				0.325 / 0.618				0.187 / 0.469				0.435 / 0.772			

Note. Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first); RRS-10 = trait rumination (mean-centered). Because of outliers, we removed four participants from the RT 1-back and d' 2-back analyses, and three participants from the RT 2-back analyses.

6. Moderated mediation analyses results

Table S3. Mediation of the effect of tDCS on total state rumination by 3back RT moderated by the RRS-10

		Model Summary			Regression coefficients				Conditional effects of trait rumination (RRS-10)					
									-1 SD		mean		+ 1SD	
		*R*²	*F*	*p*	*effect*	*SE*	*t*	*p*	*effect*	*p*	*effect*	*p*	*effect*	*p*
Direct effects														
a	tDCS → 3back RT	0.1	3.61	0.066	-22.841	27.832	-0.82	0.418						
	tDCS*RRS-10 → 3back RT				-10.13	5.326	-1.9	0.066	30.939	0.441	-22.841	0.418	-76.621	0.063
	tDCS → rumination				0.058	0.242	0.242	0.81						
	3back RT → rumination				0.004	0.001	3.16	**0.003**						
c'	tDCS*RRS-10 → 3back RT → brooding	0.31	4.23	**0.013**	0.015	0.046	0.32	0.746	-0.021	0.946	0.058	0.81	0.139	0.707
b	3back RT*RRS-10 → rumination				0.0004	0.0003	1.23	0.225	0.002	0.251	0.004	**0.003**	0.006	**0.005**
Total effect														
	tDCS → rumination	0.02	0.83	0.368	-0.154	0.257	-0.59	0.553						
c	tDCS*RRS-10 → rumination				-0.045	0.049	-0.91	0.368	0.084	0.819	-0.154	0.553	-0.393	0.292
									effect	95% CI	*effect*	95% CI	*effect*	95% CI
Index of moderated mediation														
ab (a1b1-a0b0)						NA[a]			0.08	[-0.236, 0.326]	-0.106	[-0.402, 0.147]	-0.514	[-1.124, 0.01]

Note. tDCS = tDCS condition, sham vs anodal stimulation; RRS-10 = trait rumination (mean-centered); 3back RT = average reaction times on the 3-back task.
[a] The index of moderation was not generated by MEMORE because the indirect effect is a non-linear function of the moderator.

Table S4. Mediation of the effect of tDCS on negativity by 3-back RT moderated by the RRS-10

		Model Summary			Regression coefficients				Conditional effects of trait rumination (RRS-10)					
									-1 SD		mean		+ 1SD	
		R^2	*F*	*p*	effect	*SE*	*t*	*p*	*effect*	*p*	*effect*	*p*	*effect*	*p*
Direct effects														
	tDCS → 3back RT	0.1	3.61	0.066	-22.841	27.832	-0.82	0.418						
a	tDCS*RRS-10 → 3back RT				-10.13	5.326	-1.9	0.066	30.939	0.441	-22.841	0.418	-76.621	0.063
	tDCS → negativity				-0.058	0.047	-1.23	0.228						
	3back RT → negativity				0.0002	0.0003	0.672	0.506						
c'	tDCS*RRS-10 → 3back RT → negativity	0.02	0.27	0.845	-0.002	0.009	-0.22	0.825	-0.047	0.458	-0.058	0.228	-0.069	0.343
b	3back RT*RRS-10 → negativity				0	0.0001	0.26	0.796	0.0001	0.803	0.0002	0.506	0.0003	0.524
Total effect														
	tDCS → negativity				-0.067	0.042	-1.57	0.126						
c	tDCS*RRS-10 → negativity	0.01	0.3	0.584	-0.004	0.008	-0.553	0.584	-0.043	0.483	-0.067	0.126	-0.09	0.144
									effect	95% CI	*effect*	95% CI	*effect*	95% CI
Index of moderated mediation														
a1b1-a0b0					NA[a]				0.003	[-0.058, 0.037]	-0.004	[-0.039, 0.011]	-0.021	[-0.138, 0.042]

Note. tDCS = tDCS condition, sham vs anodal stimulation; RRS-10 = trait rumination (mean-centered); 3back RT = average reaction times on the 3-back task.
[a] The index of moderation was not generated by MEMORE because the indirect effect is a non-linear function of the moderator.

Table S5. Mediation of the effect of tDCS on brooding by 3-back RT moderated by the RRS-10

		Model Summary			Regression coefficients				Conditional effects of trait rumination (RRS-10)					
									-1 SD		mean		+ 1SD	
		R^2	*F*	*p*	effect	SE	t	p	effect	p	effect	p	effect	p
Direct effects														
	tDCS → 3back RT	0.1	3.61	0.066	-22.841	27.832	-0.82	0.418						
a	tDCS*RRS-10 → 3back RT				-10.13	5.326	-1.9	0.066	30.939	0.441	-22.841	0.418	-76.621	0.063
	tDCS → brooding				0.044	0.061	0.71	0.478						
	3back RT → brooding				0.001	0.0004	2.59	0.015						
c'	tDCS*RRS-10 → 3back RT → brooding	0.33	4.72	0.008	-0.0001	0.011	-0.005	0.995	0.044	0.592	0.044	0.478	0.043	0.641
b	3back RT*RRS-10 → brooding				0.0002	0.0001	2.29	0.029	0	0.993	0.001	0.015	0.001	0.001
Total effect														
	tDCS → brooding	0.05	1.61	0.21	-0.027	0.065	-0.42	0.673						
c	tDCS*RRS-10 → brooding				-0.015	0.012	-1.27	0.213	0.056	0.548	-0.027	0.673	-0.112	0.237
									effect	95% CI	effect	95% CI	effect	95% CI
Index of moderated mediation														
a1b1-a0b0						NAa			0.0001	[-0.061, 0.047]	-0.022	[-0.082, 0.032]	-0.147	[-0.299, 0.004]

Note. tDCS = tDCS condition, sham vs anodal stimulation; RRS-10 = trait rumination (mean-centered); 3back RT = average reaction times on the 3-back task.
[a] The index of moderation was not generated by MEMORE because the indirect effect is a non-linear function of the moderator.

Table S6. Mediation of the effect of tDCS on perseveration by 3-back RT moderated by the RRS-10

		Model Summary			Regression coefficients				Conditional effects of trait rumination (RRS-10)					
									-1 SD		mean		+ 1SD	
		R^2	*F*	*p*	effect	*SE*	*t*	*p*	*effect*	*p*	*effect*	*p*	*effect*	*p*
Direct effects														
	tDCS → 3back RT	0.1	3.61	0.066	-22.841	27.832	-0.82	0.418						
a	tDCS*RRS-10 → 3back RT				-10.130	5.326	-1.9	0.066	30.939	0.441	-22.841	0.418	-76.621	0.063
	tDCS → perseveration				0.043	0.073	0.59	0.558						
	3back RT → perseveration				0.001	0.0004	3.46	**0.001**						
c'	tDCS*RRS-10 → 3back RT → perseveration	0.324	4.476	**0.01**	0.002	0.014	0.14	0.887	0.032	0.741	0.043	0.558	0.054	0.63
b	3back RT*RRS-10 → perseveration				0	0.0001	0.372	0.712	0.001	0.053	0.001	**0.001**	0.001	**0.015**
Total effect														
	tDCS → perseveration				-0.001	0.078	-0.018	0.985						
c	tDCS*RRS-10 → perseveration	0.031	0.968	0.332	-0.014	0.015	-0.984	0.332	0.076	0.496	-0.001	0.985	-0.079	0.48
									effect	95% CI	*effect*	95% CI	*effect*	95% CI
Index of moderated mediation														
a1b1-a0b0					NA[a]				0.041	[-0.074, 0.15]	-0.035	[-0.126, 0.049]	-0.132	[-0.341, 0.009]

Note. tDCS = tDCS condition, sham vs anodal stimulation; RRS-10 = trait rumination (mean-centered); 3back RT = average reaction times on the 3-back task.

[a] The index of moderation was not generated by MEMORE because the indirect effect is a non-linear function of the moderator.

Table S7. Mediation of the effect of tDCS on replaying by 3-back RT moderated by the RRS-10

		Model Summary			Regression coefficients				Conditional effects of trait rumination (RRS-10)					
									-1 SD		mean		+ 1SD	
		R^2	*F*	*p*	effect	*SE*	*t*	*p*	*effect*	*p*	*effect*	*p*	*effect*	*p*
Direct effects														
	tDCS → 3back RT	0.1	3.61	0.066	-22.841	27.832	-0.82	0.418						
a	tDCS*RRS-10 → 3back RT				-10.130	5.326	-1.9	0.066	30.939	0.441	-22.841	0.418	-76.621	0.063
	tDCS → replaying				0.027	0.067	0.4	0.691						
	3back RT → replaying				0.001	0.0004	2.93	**0.006**						
c'	tDCS*RRS-10 → 3back RT → replaying	0.27	3.47	**0.029**	0.005	0.013	0.4	0.687	-0.0009	0.992	0.027	0.691	0.055	0.594
b	3back RT*RRS-10 → replaying				0.0001	0.0001	1.048	0.303	0.0007	0.255	0.001	**0.006**	0.001	**0.01**
Total effect														
	tDCS → replaying	0.01	0.553	0.462	-0.025	0.07	-0.365	0.717						
c	tDCS*RRS-10 → replaying				-0.01	0.013	-0.744	0.462	0.027	0.785	-0.025	0.717	-0.078	0.437
									effect	95% CI	*effect*	95% CI	*effect*	95% CI
Index of moderated mediation														
a1b1-a0b0					NA[a]				0.022	[-0.059, 0.103]	-0.027	[-0.1, 0.038]	-0.129	[-0.264, 0.013]

Note. tDCS = tDCS condition, sham vs anodal stimulation; RRS-10 = trait rumination (mean-centered); 3back RT = average reaction times on the 3-back task.
[a] The index of moderation was not generated by MEMORE because the indirect effect is a non-linear function of the moderator.

Table S8. Mediation of the effect of tDCS on criticism by 3-back RT moderated by the RRS-10

		Model Summary			Regression coefficients				Conditional effects of trait rumination (RRS-10)					
									-1 SD		mean		+ 1SD	
		R^2	*F*	*p*	effect	*SE*	*t*	*p*	*effect*	*p*	*effect*	*p*	*effect*	*p*
Direct effects														
	tDCS → 3back RT	0.1	3.61	0.066	-22.841	27.832	-0.82	0.418						
a	tDCS*RRS-10 → 3back RT				-10.130	5.326	-1.9	0.066	30.939	0.441	-22.841	0.418	-76.621	0.063
	tDCS → criticism				0.002	0.056	0.04	0.964						
	3back RT → criticism				0.0008	0.0003	2.24	**0.033**						
c'	tDCS*RRS-10 → 3back RT → criticism	0.17	1.94	0.14	0.01	0.01	0.92	0.361	-0.05	0.506	0.002	0.964	0.055	0.517
b	3back RT*RRS-10 → criticism				0.0001	0.0001	0.89	0.379	0.0004	0.42	0.0008	**0.033**	0.001	**0.039**
Total effect														
	tDCS → criticism	0	0.0001	0.992	-0.032	0.055	-0.59	0.557						
c	tDCS*RRS-10 → criticism				0.0001	0.01	0.01	0.992	-0.033	0.675	-0.032	0.557	-0.032	0.685
									effect	95% CI	*effect*	95% CI	*effect*	95% CI
Index of moderated mediation														
a1b1-a0b0						NA[a]			0.013	[-0.06, 0.068]	-0.017	[-0.076, 0.020]	-0.084	[-0.23, 0.02]

Note. tDCS = tDCS condition, sham vs anodal stimulation; RRS-10 = trait rumination (mean-centered); 3back RT = average reaction times on the 3-back task.
[a] The index of moderation was not generated by MEMORE because the indirect effect is a non-linear function of the moderator.

7. Post-hoc exploratory analyses

The full models including the stress score and 3-back RT performed better. The full model including the stress score and 3-back RT explained 33.5% of the variance in state rumination (see Table S9). The main effect of 3-back RT was significant ($t(1,36.09) = 2.58$, $p = .014$), but not the effect of stress ($t(1, 53.8) = 1.74$, $p = 0.096$). These results indicate that slower reaction times during the N-back were associated with higher total state rumination (faster reaction time [-1SD = 565 ms] = 1.76/5 total state rumination; slower reaction time [+1SD = 842 ms] = 2.46/5 total state rumination). Note that the full model had a significantly better model fit compared to the model without the stress score and 3-back RT ($Chisq(2) = 9.57$, $p = 0.008$), but the full model was not significantly better than a model with only N-back RT without the stress score ($Chisq(1) = 3.16$, $p = 0.065$).

Related to our hypothesis about the features of rumination, only one pattern emerged from investigating each feature of rumination separately. Notably, like in our first analyses (see Table 2 of the manuscript), a considerable amount of variance of negativity and self-criticism was explained by random effects and only little was explained by fixed effects as reflected in the difference between marginal and conditional R^2 (see Tables S10–S14). This further suggests that these two features are more related to differences between participants rather than explained by predictors alone, even when also accounting for stress and 3-back RT.

In summary, 3-back RT and not stress was the strongest predictor of total rumination. One possible explanation to the mixed effect of stress is that the backward counting task was not sufficiently stressful, especially since participants performed it twice.

Table S9. Effect of tDCS stimulation, 3-back Reaction Time, stress, and trait rumination on total state rumination

	Total Rumination					Total Rumination					Total Rumination				
Predictors	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*
(Intercept)	2.1	0.12	16.8	**<0.001**	29	2.1	0.11	18.65	**<0.001**	27.98	2.1	0.11	19.22	**<0.001**	27.28
Stimulation order	0.07	0.13	0.56	0.582	29	0	0.12	0	0.996	28.46	-0.01	0.12	-0.06	0.952	27.82
Session	0.43	0.1	4.11	**<0.001**	30	0.25	0.13	1.99	0.052	47.55	0.22	0.13	1.71	0.094	46.01
RRS-10	0.04	0.03	1.56	0.13	29	0.04	0.02	1.6	0.121	28	0.04	0.02	1.8	0.082	27.46
Condition	-0.1	0.1	-0.99	0.328	30	-0.06	0.11	-0.55	0.585	31.03	-0.04	0.11	-0.34	0.733	30.81
3-back RT						3.94	1.55	2.53	**0.016**	37.73	3.91	1.51	2.58	**0.014**	36.09
Stress during stressor											2.34	1.38	1.69	0.096	53.8
Marginal R^2 / Conditional R^2	0.215 / 0.350					0.289 / 0.326					0.319 / 0.335				
AIC	194.406					187.935					184.637				
log-Likelihood	-90.203					-85.967					-83.318				

Note. N = 32; Observations = 64; Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first; RRS-10 = trait rumination (mean-centered); 3-back RT = average reaction times on the 3-back task (mean-centered); Stress during stressor = stress felt during the backward counting task

Table S10. Effect of tDCS stimulation, 3-back Reaction Time, stress, and trait rumination on negativity

	Negativity					Negativity					Negativity				
Predictors	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*
(Intercept)	0.31	0.04	8.52	**<0.001**	29	0.31	0.03	9.1	**<0.001**	26.53	0.31	0.03	9.12	**<0.001**	26.81
Stimulation order	0.01	0.04	0.16	0.877	29	-0.01	0.04	-0.17	0.866	27.32	-0.01	0.04	-0.17	0.868	27.6
Session	0.03	0.02	1.61	0.117	30	0	0.03	0.12	0.904	51.38	0.01	0.03	0.22	0.827	49.43
RRS-10	0.02	0.01	2.06	**0.049**	29	0.01	0.01	2.12	**0.043**	26.55	0.01	0.01	2.05	0.051	27
Condition	-0.04	0.02	-1.73	0.094	30	-0.03	0.02	-1.27	0.213	30.1	-0.03	0.02	-1.37	0.18	30.09
3-back RT						0.66	0.43	1.52	0.134	47.54	0.71	0.44	1.63	0.111	45.33
Stress during stressor											-0.32	0.35	-0.93	0.359	55.3
Marginal R^2 / Conditional R^2	0.130 / 0.585					0.169 / 0.535					0.182 / 0.538				
AIC	25.922					25.783					27.187				
log-Likelihood	-5.961					-4.891					-4.594				

Note. N = 32; Observations = 64; Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first; RRS-10 = trait rumination (mean-centered); 3-back RT = average reaction times on the 3-back task (mean-centered); Stress during stressor = stress felt during the backward counting task.

Table S11. Effect of tDCS stimulation, 3-back Reaction Time, stress, and trait rumination on brooding

	Brooding					Brooding					Brooding				
Predictors	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*
(Intercept)	0.39	0.03	12.09	**<0.001**	0.39	0.39	0.03	13.63	**<0.001**	58	0.39	0.03	13.92	**<0.001**	57
Stimulation order	0.02	0.03	0.48	0.632	0.02	-0.01	0.03	-0.26	0.798	58	-0.01	0.03	-0.32	0.748	57
Session	0.09	0.03	3.04	**0.005**	0.09	0.03	0.03	0.95	0.349	58	0.02	0.03	0.66	0.514	57
RRS-10	0.02	0.01	2.85	**0.008**	0.02	0.02	0.01	3.04	**0.004**	58	0.02	0.01	3.28	**0.002**	57
Condition	-0.02	0.03	-0.66	0.512	-0.02	0	0.03	-0.17	0.864	58	0	0.03	0.05	0.962	57
3-back RT						1.29	0.39	3.27	**0.002**	58	1.28	0.39	3.31	**0.002**	57
Stress during stressor											0.67	0.36	1.88	0.066	57
Marginal R^2 / Conditional R^2	0.220 / 0.282					0.333 / NA					0.366 / NA				
AIC	39.093					31.306					30.064				
log-Likelihood	-12.547					-7.653					-6.032				

Note. N = 32; Observations = 64; Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first; RRS-10 = trait rumination (mean-centered); 3-back RT = average reaction times on the 3-back task (mean-centered); Stress during stressor = stress felt during the backward counting task.

Table S12. Effect of tDCS stimulation, 3-back Reaction Time, stress, and trait rumination on perseveration

	Perseveration					Perseveration					Perseveration				
Predictors	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*
(Intercept)	0.52	0.03	17.29	**<0.001**	59	0.52	0.03	17.22	**<0.001**	58	0.52	0.03	17.22	**<0.001**	58
Stimulation order	0.05	0.03	1.49	0.142	59	0.04	0.03	1.27	0.209	58	0.04	0.03	1.27	0.209	58
Session	0.13	0.03	4.41	**<0.001**	59	0.12	0.04	3.36	**0.001**	58	0.12	0.04	3.36	**0.001**	58
RRS-10	0	0.01	0.12	0.909	59	0	0.01	0.08	0.935	58	0	0.01	0.08	0.935	58
Condition	-0.01	0.03	-0.3	0.765	59	-0.01	0.03	-0.19	0.852	58	-0.01	0.03	-0.19	0.852	58
3-back RT						0.29	0.42	0.7	0.489	58	0.29	0.42	0.7	0.489	58
Stress during stressor											0.82	0.37	2.21	**0.031**	57
Marginal R^2 / Conditional R^2	0.257 / NA					0.260 / NA					0.311 / NA				
AIC	36.767					38.188					35.575				
log-Likelihood	-11.384					-11.094					-8.788				

Note. N = 32; Observations = 64; Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first; RRS-10 = trait rumination (mean-centered); 3-back RT = average reaction times on the 3-back task (mean-centered); Stress during stressor = stress felt during the backward counting task.

Table S13. Effect of tDCS stimulation, 3-back Reaction Time, stress, and trait rumination on replaying

	Replaying					Replaying					Replaying				
Predictors	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*
(Intercept)	0.46	0.04	12.76	**<0.001**	29	0.47	0.03	13.43	**<0.001**	28.04	0.47	0.03	15.16	**<0.001**	26.67
Stimulation order	0	0.04	-0.06	0.949	29	-0.02	0.04	-0.47	0.641	28.6	-0.02	0.03	-0.64	0.527	27.23
Session	0.11	0.03	3.91	**<0.001**	30	0.08	0.04	2.12	**0.039**	49.3	0.06	0.04	1.65	0.106	46
RRS-10	0	0.01	-0.47	0.64	29	0	0.01	-0.58	0.569	28.06	0	0.01	-0.36	0.72	26.85
Condition	-0.02	0.03	-0.69	0.497	30	-0.01	0.03	-0.36	0.724	31.25	0	0.03	0.02	0.981	30.2
3-back RT						0.81	0.47	1.74	0.09	40.15	0.82	0.42	1.93	0.061	36
Stress during stressor											1.17	0.38	3.04	**0.004**	54.36
Marginal R^2 / Conditional R^2	0.163 / 0.354					0.204 / 0.336					0.309 / 0.347				
AIC	45.436					44.256					37.986				
log-Likelihood	-15.718					-14.128					-9.993				

Note. N = 32; Observations = 64; Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first; RRS-10 = trait rumination (mean-centered); 3-back RT = average reaction times on the 3-back task (mean-centered); Stress during stressor = stress felt during the backward counting task.

Table S14. Effect of tDCS stimulation, 3-back Reaction Time, stress, and trait rumination on self-criticism

	Self-Criticism					Self-Criticism					Self-Criticism				
Predictors	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*	*B*	*SE*	*t*	*p*	*df*
(Intercept)	0.41	0.04	11.56	**<0.001**	29	0.41	0.04	11.72	**<0.001**	28.25	0.41	0.04	11.62	**<0.001**	27.96
Stimulation order	0.01	0.04	0.17	0.87	29	0	0.04	-0.08	0.937	28.94	0	0.04	-0.08	0.937	28.68
Session	0.06	0.03	2.5	**0.018**	30	0.04	0.03	1.24	0.22	51.2	0.04	0.03	1.21	0.233	49.32
RRS-10	0.01	0.01	1.15	0.261	29	0.01	0.01	1.11	0.275	28.27	0.01	0.01	1.11	0.278	28.16
Condition	-0.02	0.03	-0.81	0.426	30	-0.01	0.03	-0.57	0.575	31.67	-0.01	0.03	-0.55	0.589	31.36
3-back RT						0.49	0.46	1.07	0.291	44.37	0.49	0.47	1.05	0.3	42.62
Stress during stressor											0.04	0.39	0.09	0.929	56.88
Marginal R^2 / Conditional R^2	0.090 / 0.398					0.108 / 0.392					0.106 / 0.391				
AIC	36.355					36.933					38.972				
log-Likelihood	-11.177					-10.467					-10.486				

Note. N = 32; Observations = 64; Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first; RRS-10 = trait rumination (mean-centered); 3-back RT = average reaction times on the 3-back task (mean-centered); Stress during stressor = stress felt during the backward counting task.

8. Bayesian analyses results with the features of rumination

Table S15 presents the results of the Bayesian model averaging procedure of Bayesian mixed models with "participants" as the random variable, always accounting for at least "session" as a predictor, with the denominator being a null model. The inclusion bayes factors indicate how much more likely the observed data is under a model with a term compared to a model without this term.

First, for all features of rumination except negativity, there is substantial evidence indicating that the condition (active vs sham tDCS) or an interaction between condition and trait rumination do not explain the observed data (all BFs <= .33). There was very strong evidence for Session as a predictor of perseveration (BF = 59.61). There was strong evidence for ID as a predictor of negativity (BF = 13.85) whereas there was substantial evidence against ID as a predictor of brooding, replaying, perseveration. And there was evidence against stimulation order as a predictor of brooding and replaying. Second, there was substantial to very strong evidence for 3-back RT as a predictor of replaying (BF = 3.02), and brooding (BF = 108.82). In contrast, there was strong evidence for stress as only a predictor of replaying (BF = 21.15).

Table S15. Inclusion Bayesian Factors for rumination features

Predictor	prior P()	Brooding post. P()	Brooding Incl. BF	Negativity post. P()	Negativity Incl. BF	Replaying post. P()	Replaying Incl. BF	Perseveration post. P()	Perseveration Incl. BF	Self-Criticism post. P()	Self-Criticism Incl. BF
Condition	0.6	0.25	**0.22**	0.44	0.52	0.23	**0.19**	0.22	**0.19**	0.26	**0.24**
RRS-10	0.6	0.97	**23.64**	0.74	1.94	0.25	**0.22**	0.27	**0.24**	0.44	0.52
Session	0.5	0.32	0.48	0.30	0.43	0.69	2.22	0.98	**59.61**	0.53	1.12
ID	0.5	0.05	**0.05**	0.93	**13.85**	0.14	**0.17**	0.03	**0.03**	0.64	1.74
3-back RT	0.5	0.99	**108.82**	0.70	2.38	0.75	**3.02**	0.38	0.61	0.59	1.46
Stress during stressor	0.5	0.60	1.49	0.32	0.46	0.95	**21.15**	0.75	2.96	0.27	0.37
Condition*RRS-10	0.2	0.06	**0.24**	0.09	0.37	0.02	**0.09**	0.02	**0.09**	0.04	**0.18**
Stimulation order	0.5	0.23	**0.3**	0.29	0.41	0.23	**0.3**	0.38	0.6	0.25	**0.33**

Note. Incl. BF = indicates how much more likely the observed data is under a model with this term compared to a model without this term; prior P() = prior probabilities; post. P() = posterior (inclusion) probabilities (i.e., the model-average probability of including a certain predictor in the model, given the observations); Condition = tDCS condition, sham vs anodal stimulation; Stimulation order = whether participants received sham or anodal stimulation first); RRS-10 = trait rumination (mean-centered). Inclusion bayes factors higher than 3 (i.e., substantial evidence for including this term in the model) and lower than 1/3 (i.e., substantial evidence against including this term in the model) are in bold.

List of Tables and Figures

Tables

Figures