Executive Functioning as a Predictor of Physiological and Subjective Acute Stress Responses in Non-Clinical Adult Populations: A Systematic Literature Review and Meta-Analysis

Pre-Print Version

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Author Note

All data sets, scripts, and supplementary materials used for the meta-analysis are available on OSF (https://osf.io/h9pzm/). The study protocol (ID: CRD42019122297) was published on PROSPERO and is accessible online (https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42019122297).

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Abstract

GRIMM, E., S. Agrigoroaei, N. Rohleder, and L. Becker. Executive Functioning as a Predictor of Physiological and Subjective Acute Stress Responses in Non-Clinical Adult Populations: A Systematic Literature Review and Meta-Analysis. NEUROSCI BIOBEHAV REV XX(X) XXX-XXX, 2021. – The goal of this systematic review and meta-analysis was to evaluate whether executive functioning predicts subsequent acute stress responses. A systematic search (conducted May 22nd–30th, 2019; updated April 4th, 2020) on Cochrane, OpenGray, Proquest Dissertations and Thesis Global, PsycInfo, Pubmed, Scopus, and Web of Science revealed 26 correlational and five interventional studies. For quality appraisal, we used the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies and the BIOCROSS Tool for correlational studies, and the Revised Cochrane Risk-of-bias Tool for Randomized Trials for interventional designs. Attentional control was most consistently associated with acute stress. A robust variation estimation meta-analysis, conducted where sufficient data was available, revealed a small, significant, and negative correlation between higher working memory and subsequent lower cortisol reactivity to an acute stressor (r= -.09 p=.025, 95% CI [-0.15, -0.02]). These results highlight the role of executive functioning for heathier stress responses, the scarcity of relevant data, and the need for both interventional designs and the consideration of mediators and moderators to understand underlying mechanisms.

Keywords: executive functioning, acute stress, systematic literature review, meta-analysis, attentional control, working memory, inhibition, flexibility, updating, planning, cortisol, heart rate, subjective stress

1. Introduction

Adaptive from an evolutionary point of view, acute stress responses represent a common experience for individuals in the 21st century. The exposure to events perceived as threatening generates a series of sequential physiological and subjective-cognitive reactions enabling the individual to adapt and to implement appropriate coping strategies. The first, immediate stress response is the activation of the sympathetic nervous system (SNS), the so-called “fight-or-flight” response, which releases the hormones epinephrine and norepinephrine and increases both heart rate and blood pressure (Selye, 1946). The second, delayed response is the activation of the hypothalamic-pituitary adrenal (HPA) axis several minutes later, which leads to the secretion of the stress hormone cortisol from the adrenal cortex (Fulford & Harbuz, 2005; Selye, 1946). With a further delay, complex effects on the immune system are activated, such as an up-regulation of some components (i.e., inflammatory pathways) and down-regulation of others (i.e., cellular immunity; Chrousos, 2009; Morey et al., 2015). In terms of psychological responses, measurements often include perceptions of subjective stress, pressure, threat, and lack of personal control in light of one’s personal resources.

Beyond this renowned phase of stress reactivity, it is important to distinguish four additional phases of the stress response that enable humans to respond adequately to stressful events. Anticipatory stress refers to the physiological and subjective responses observed after being informed about a future stressful situation, ahead of actual exposure (Engert et al., 2013). Exposure is defined as the likelihood of being confronted with an event perceived as stressful given one’s personal vulnerability and resilience factors (Koffer et al., 2016). The recovery phase, following initial reactivity, leads to the return to baseline of the activated stress systems and allows for homeostasis. Once the threat has passed, the parasympathetic nervous system

(PNS) is also implicated in reducing one's heart rate. Finally, habituation is characterized by an overall lower stress response following repeated exposure to the same, or similar, acute stressor (Grissom & Bhatnagar, 2009; Thompson & Spencer, 1966).

While these biological and psychological stress responses can be considered adaptive, their prolonged or repeated activation has deleterious long-term consequences. These include higher allostatic load, the cumulative wear-and-tear of multiple physiological systems, and, ultimately, serious health problems (McEwen, 1998). Thus, identifying modifiable personal factors that limit excessive stress responses represents an important research goal.

1.1. Executive Functioning

Recent empirical evidence suggests that executive functioning may play a protective role for stress regulation. Executive functioning is a higher-order neurocognitive control-system that enables individuals to organize their actions, to flexibly engage in goal- and future-directed behaviors, and to successfully adapt to changing environments (Jurado & Rosselli, 2007). As a multidimensional overarching construct, it comprises individual facets commonly identified as inhibition, flexibility, updating, working memory, attentional control, and planning (Diamond, 2013; Friedman & Miyake, 2017; Snyder et al., 2015). Inhibition is the ability to prevent predominant, automatic, or inadequate responses. Flexibility, or set-shifting, is the capacity to switch between tasks, operations, actions, or cognitions. Verbal fluency is also considered to capture cognitive flexibility, reflecting the access to one's lexical repertoire and semantic memory, as well as the generation of new ideas and language content (Rende et al., 2002). Working memory updating is the constant monitoring of incoming information in working memory (a limited capacity cognitive system responsible for the temporary storage and processing of information; Baddeley, 2002), and the removal of content no longer relevant to the task. Attentional capacities can be divided into top-down and bottom-up processes. The former, otherwise known as attentional control, is one's ability to engage – and to maintain – one's attention upon information that is relevant to current tasks or goals (Engle, 2018). In the latter, a stimulus undergoes biased processing as a result of its particular salience (i.e., a specific characteristic such as stress-related information; Posner et al., 1984). Finally, mental planning enables individuals to generate roadmaps to reach specific goals, laying the foundations for goal-directed behavior.

1.2. Executive Functioning and Acute Stress

The association between executive functioning and stress has been predominantly documented by studies examining the cognitive impairments resulting from acute stress inductions or prolonged stressful experiences. For example, recent meta-analyses have investigated the effects of acute (e.g., Shields et al., 2016) and chronic stress (Allen et al., 2017) upon executive functioning. The reverse association, where executive functioning represents a protective factor for adaptive stress responses, has not been the object of extensive, integrative research, systematic review, or meta-analytical efforts, despite existing theoretical accounts.

Differences in executive functioning emerging from genetic, neuroanatomical, physiological, cognitive, and environmental factors may represent a source of resilience for the different stress phases (for the theoretical model, see Williams et al., 2009). In their stress optimization model, Crum and colleagues' (2020) similarly name several processes involved in optimizing stress regulation, which fundamentally require executive functioning. For instance, inhibition, task switching, updating, attentional control, and planning abilities are required for (a) learning to select stressful situations that align with one's goals, and to disengage when this fails to be the case, (b) deploying one's attention away from negative-related stimuli and towards goal-specific information, and (c) using reappraisal techniques.

Emerging behavioral and physiological research on the subject provides a promising opening on this research question. A study on frail individuals reported that the likelihood of being exposed to potential stressful situations depended upon baseline executive functioning, with a focus on individuals' abilities to plan their daily activities (Roiland et al., 2015). Another study revealed that higher efficiency of attention alerting and orienting after exposure to negative, stressful cues led to increases in subsequent cytokine responses (Maydych et al., 2018).

To summarize, limited work is currently available to identify the relevant, specific executive functioning facets and stress phases involved, as well as candidate mediators and moderators implicated. Given the age-related changes observed for both executive functioning (Singh et al., 2012) and stress reactivity (Uchino et al., 2005), considering chronological age as a moderator is necessary to better understand how executive functioning variations influence physiological and psychological stress responses among younger, middle-aged, and older adults.

1.3. Current Study

In light of the potential benefits of higher executive functioning for stress, and the current lack of comprehensive approaches allowing for a precise, data-driven examination of these effects, we sought to systematically review the association between executive functioning and acute stress in healthy adults, and to quantify its strength using a meta-analysis. Clarifying the role of executive functioning in such populations could guide future developments of *preventive* stress interventions with long-term health benefits. Moreover, we strived to provide insight on the role of individual *baseline* executive functioning facets, incorporating results from correlational, longitudinal, and interventional studies, where executive functioning was either tested or experimentally manipulated *ahead* of an acute stressor. The integration of these approaches enables greater awareness regarding the operationalization of this research question in the literature, while shedding light on existing experimental manipulations that confirm the relevance of the cause-and-effect relationship between executive functioning and stress regulation.

Three pre-registered research questions were derived from this goal. First, do distinct executive functioning facets (i.e., inhibition, flexibility, updating, working memory, attentional control, and planning) differ in their effect upon acute stress responses? Second, to what extent does this association depend upon the stress indicators (i.e., both self-report and physiological measures) and phases (i.e., anticipation, exposure, reactivity, recovery, and habituation) considered? Third, does the association vary as a function of age?

Following the initial systematic literature review, we aimed to conduct a correlational meta-analysis using robust variations estimation method when sufficient data was available. To decrease heterogeneity regarding the cognitive tasks, stress phases, and stress outcomes, separate databases were created for the different stress phases, which were further divided according to executive functioning facets targeted and stress outcomes considered. Based on recent literature and previous meta-analyses on stress and executive functioning (Laborde et al., 2017; Shields et al., 2016; Zänkert et al., 2019; for a recent review, see Shields, 2020), we included other important moderators of the stress-cognition literature, including participant characteristics (sex, smoking, medication use), task-related aspects (presence/absence of emotional stimuli, performance-based vs. time-based indicators), the type and severity of the acute stressor, time of day for testing, and publication year.

2. Methods

The current systematic review and meta-analysis was conducted in accordance with the PRISMA guidelines (Moher et al., 2009; see Supplementary Materials 1 on the Open Science Framework, OSF). The study protocol (ID: 42019122297) was published on PROSPERO on February 6th, 2019 and is accessible online (https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42019122297). All data sets, scripts, and supplementary materials used for the meta-analysis are available on OSF (https://osf.io/h9pzm/).

2.1. Eligibility Criteria

We included studies using the following criteria: (1) design: randomized trials, longitudinal studies, or cross-sectional studies in which executive functioning (see the "information sources" subsection for a list of eligible facets) was assessed *before* the administration of a stressor or a measurement of acute stress; (2) sample population: healthy adult populations aged over 18; (3) intervention (if present): inclusion of at least one passive or active control group; (4) outcomes: both physiological and subjective (i.e., self-reported stress, tension or nervousness levels on a scale from 0-10) measures of stress. These included responses of the (i) HPA axis (e.g., cortisol area under the curve with respect to ground, AUC_g, and with respect to increase, AUC_i), (ii) inflammatory system (e.g., C-reactive protein, interleukin-6), (iii) cardiovascular system (e.g., resting diastolic (DBP) and systolic (SBP) blood pressure, pulse pressure, heart rate), (iv) SNS (e.g., norepinephrine, epinephrine, alpha-amylase, skin conductance), and (v) PNS (e.g., heart rate variability, HRV). The exclusion criteria comprised (a) literature reviews, uncontrolled intervention studies, and case studies; (b) clinical populations (e.g., diagnosis of mood disorders, dementia, or chronic health problems); (c) younger populations (children or adolescents); (d) interventional studies focusing on training cognitive abilities other than executive functioning (such as memory or processing speed); (e) outcome measures of anxiety, which incorporate broader processes like worry (e.g., Shin & Liberzon, 2010); and (f) studies not written in English. There were no limitations regarding the year or type of publication.

2.2. Information Sources and Search

Between May 22nd and 30th, 2019, we conducted a systematic literature review of studies available on Cochrane, OpenGray, Proquest Dissertations and Thesis Global, PsycInfo, Pubmed, Scopus, and Web of Science. The searching process involved combining terms pertaining to executive functioning, stress outcomes, and the presence of an intervention. Executive functioning was captured through the keywords “executive function*”, “executive control”, “cognitive function*”, “cognitive control”, “cognitive flexibility”, “fluency”, “attention* control”, “selective attention”, “inhibit* control”, “inhibition”, “planning”, “shifting”, “switching”, “updating”, and “working memory”. The stress terms comprised “stress exposure”, “stress anticipat*”, “anticipatory stress”, “stress react*”, “stress recovery”, “stress habituat*”, “stress adaptat*”, “repeated stress”, “stress regulation”, “acute stress”, “physiological stress”, “psychological stress”, “self-reported stress”, “subjective stress”, “self-rated stress”, “perceived stress”, “cortisol”, “c-reactive protein”, “interleukin-6”, “heart rate”, “cardiovascular”, “blood pressure”, “norepinephrine”, “epinephrine”, “alpha-amylase”, “skin conductance”, “glucorticoid*”, and “frequency spectral power”. Finally, we entered the terms “intervention”, “modification”, “program”, and “training” when seeking cognitive interventions. The full search strings for each database can be found in Supplementary Materials 2 on OSF.

2.3. Study Selection

Using EndNote, duplicates were removed and two reviewers (a PhD candidate and a post-doctoral researcher) independently screened titles and abstracts. Cohen's kappa was fair (k = 0.24; McHugh, 2012). Given the high number of abstracts to screen (see Figure 1 for the PRISMA flow chart), this led to the over prevalence of one category response, namely both raters deciding to exclude a study. Highly dependent upon response prevalence, the kappa statistic may lead to low levels of reliability despite a very high percentage agreement between raters (Cargo et al., 2015; Viera & Garrett, 2005). In light of this, we additionally report the latter, which was almost perfect (99.54%).

Once the full texts were retrieved, they were uploaded to the Covidence online platform (www.covidence.org), which was employed for the remaining steps of the systematic review. Any disagreements between the two raters were resolved through discussion with a third reviewer (a university professor with a PhD degree). Reference lists from articles were retrieved and searched for additional studies. Furthermore, to reduce publication bias, we asked the authors of articles included in the full text extraction phase for any additional studies or unpublished data they might be aware of. Two authors responded favorably, providing relevant papers that are included in the current systematic literature review. On April 4th, 2020, a search update was conducted using the same databases, search strings, screening, extraction, and reference list search procedures.

2.4. Data Extraction

The two reviewers followed a standardized, pre-piloted extraction form to extract data pertaining to study identification (e.g., year, publication type, sponsorship source, country, setting), methods (e.g., design, executive functioning and stress measurements, stress phase, included covariates, stressor type), population (inclusion and exclusion criteria, sample sizes, baseline characteristics), interventional details (where relevant: setting, frequency, duration, attendance, dropout), and any reported relationship between executive functioning and acute stress outcomes. Inter-rater reliability was assessed using the intra-class correlation and Cohen's kappa for continuous and categorical variables, respectively. If multiple reports of a study existed, we selected the most recently published article. Cohen's kappa was good ($k = 0.76$), while both intra-class correlations and percentage agreement were high ($ICC = 0.99$; 88.43%).

All authors whose studies were included following the full text extraction stage were contacted twice to complete information such as the nature and the distribution of the sample, medication use, or smoking status of the participants. We also asked for specific correlations between baseline executive functioning facets and the *change* in at least one measure of physiological or subjective stress response, tailoring the requests to the study design and our definitions of stress anticipation, exposure, reactivity, recovery, or habituation (see Table 1).

For studies in which participants were subjected to either a stressor or a control condition, we requested the correlations for the stress group, only. If we did not hear back from the authors, their data – where relevant – was retained for the qualitative synthesis whilst excluded from the meta-analysis. The asterisks in Table 2 mark the studies considered for the meta-analysis.

2.5. Risk of Bias in Individual Studies

To assess risk of bias, we used two separate scales for cross-sectional and interventional studies. For the former, the same two independent raters used a modified version of the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies (National Institute of Health, 2014) and the "Biomarker Measurement" domain of the BIOCROSS Quality Appraisal

Tool for Cross-sectional Studies using Biomarker Data (Wirsching et al., 2018; see Supplementary Materials 3 for further details regarding these modified scales).

For interventional studies, the Revised Cochrane Risk-of-bias Tool for Randomized Trials (RoB 2; Sterne et al., 2019) was also used in combination with the BIOCROSS biomarker measurement domain. The RoB 2 evaluates five types of biases, arising from (a) the randomization process, (b) deviations from intended interventions, (c) missing outcome data, (d) outcome measurement, and (e) selection of the reported results. Each domain comprises sub-components in which raters must answer “yes”, “probably yes”, “no”, “probably no”, or “not applicable”. These decisions follow an algorithm to generate a final rating at the domain level, specifying whether a study presents a low risk of bias, some concerns, or high risk. These grids were tested and discussed on a sub-sample of four studies, before full quality appraisal completion. Cohen’s kappa indicated good agreement (k=0.74) while the percent agreement reached 84.32%.

2.6. Meta-Analysis Procedure

2.6.1. Coding of Variables

The first author repeated the coding procedure three times, treating the different stress phases in separate databases. Based on existing literature, each cognitive task was labeled as measuring a specific executive functioning facet. The moderators were as follows: executive functioning measure (performance-based vs. time-based), presence or absence of emotional stimuli, stress indicator (e.g., cortisol, alpha-amylase), overall stress outcome (physiological vs. subjective), average age, percentage of female participants, presence or absence of medication use, smoking status (smokers excluded from study vs. not), publication year, and time of day during which participants were tested (morning, afternoon, or all day). In addition, we defined the stressor type and severity following Shields and colleagues (2016). “Social” stressors included a social evaluation but lacked any component of pain (e.g., the Trier Social Stress Test, TSST; Kirschbaum et al., 1993). “Pain” stressors lacked a social evaluation but comprised an element of pain administration (e.g., the Cold Pressor Task, CPT). “Cognitive” stressors included a cognitive task as stressor, without the pain or social components. Finally, “hybrid” tasks included any mixture of these three types of tasks. The severity of the stressor was coded as low (0) if it did not include a social, nor a pain component (e.g., cognitive stressor such as the Paced Auditory Serial Addition Test, PASAT; Gronwall, 1977). Moderate-low stressors (1) comprised either one element of social evaluation or pain (e.g., CPT). Moderate stressors (2) applied pain and included one social-evaluative element (e.g., Socially-Evaluated Cold Pressor Task, SECPT; Schwabe & Schächinger, 2018). Moderate-high stressors (3) included two elements of socio-evaluative measures (e.g., the TSST).

2.6.2. Computing Effect Sizes

As the heterogeneity among study designs did not allow for the direct computation of effect sizes of comparable data, we only included Pearson’s product-moment correlation coefficient *r* we received from authors by email. Where relevant, correlations were inversed to represent a correlation between *better* executive functioning and change in a stress measure before (anticipation), during (reactivity), and following the stressor (recovery). Moreover, while increase in cortisol, heart rate, or blood pressure are synonyms of increased stress during reactivity, the opposite is true for specific HRV measures such as High Frequency power HRV (HF-HRV) and Root Mean Square of the Successive Differences (RMSSD; Kim et al., 2018). Any correlation pertaining to the latter were further inversed to enable appropriate comparison of effect sizes. All recovery correlations were further inversed to represent *faster* recovery (i.e., faster decreases in cortisol and faster increases in HF-HRV during the recovery period). We did not conduct a meta-analysis on interventional studies, as they varied considerably in terms of training administered and stress outcomes evaluated (see Table 3).

2.6.3. Data Analyses

2.6.3.1. Main Analyses.

We completed data analysis on RStudio Version 1.4.1103. The script and all databases are available on OSF. Pearson's product-moment correlation coefficient *r* were transformed using Fisher's Z, as recommended (Borenstein et al., 2011). Based on the received data, we created three separate databases for anticipation, reactivity, and recovery. Given that physiological and subjective responses rarely correlate (e.g., Hellhammer & Schubert, 2012), and that executive functioning facets are conceptually different, we further divided the databases according to specific facets and stress outcomes.

Common meta-analytical approaches assume that the effect sizes are independent. However, given that both executive functioning facets and stress outcomes involve various assessment types, most authors provided multiple effect sizes per study. To handle the dependency between these – and to avoid losing information or increasing the likelihood of Type I errors by aggregating them (Hedges, 2007) – it is recommended to apply a robust variation estimation method (RVE; Fisher & Tipton, 2015; Hedges et al., 2010) or a three-level meta-analysis (Cheung, 2014, 2019; Konstantopoulos, 2011). For meta-analyses of a limited number of studies (< 25), multi-level models tend to underestimate variances, thereby leaving RVE as the preferred choice (for recommendations, see Moeyaert et al., 2017; Scammacca et al., 2014).

To implement RVE, we used the *robu*() function of the *robumeta* package (Fisher & Tipton, 2015). RVE estimates an overall effect size as a weighted mean of the observed effect sizes across studies, even when information regarding effect size covariance is missing. We applied small-sample adjustments for estimates and degrees of freedom (*df*), as recommended when the study sample amounts to less than 40 studies (Tipton, 2015). The ρ was set to the recommended level of 0.80 (Tanner-Smith et al., 2016). The *dfs* for all analyses were estimated using a Satterthwaite approximation, where $df = 2/cv^2$ and *cv* represents the coefficient of variation. Given that this approximation holds only if the degrees of freedom are above four (Tanner-Smith et al., 2016), we only reported significant effect sizes when this condition was met, and when $p<.05$. We performed Grubbs' test to detect the presence of outliers and planned to run sensitivity analyses with and without outliers should the test be significant.

2.6.3.2. Heterogeneity.

Heterogeneity was evaluated using both tau^2, which represents the between-study variance (Hedges et al., 2010), and with I^2, which quantifies variance in effect sizes as a result of effect size heterogeneity rather than sampling error (Borenstein et al., 2017). There is no heterogeneity when tau^2 equals zero (Quintana, 2015). In addition, low, moderate, and high variance can be identified when I^2 is 25, 50, and 75, respectively (Higgins et al., 2003).

2.6.3.3. Moderator Analyses.

We planned to perform meta-regression models on the main relationship between executive functioning and stress using RVE. We evaluated the effect of each moderator separately. Continuous predictors were directly entered into the model, as were two-level dummy-coded categorical predictors. We planned to use the *clubSandwich* package to run the Wald statistic to assess the significance of multi-level categorical predictors.

2.6.3.4. Publication Bias.

The *robumeta* package does not currently enable the evaluation of funnel plots and funnel plot asymmetry when several effect sizes are nested within studies. Thus, we conducted small-sample bias analyses on the aggregated effect sizes per study using the *metacor* function of the *meta* package (Balduzzi et al., 2019). We visualized contour-enhanced funnel plots (Peters et al., 2008) and conducted both Egger's test of the intercept (Egger et al., 1997) using *dmetar* (Harrer et al., 2019) and Duval & Tweedie's trim-and-fill procedure (Duval & Tweedie, 2000). We searched for outliers and influential cases using the aggregated databases.

3. Results

3.1. Study Selection and Characteristics

As illustrated in the PRISMA flowchart (Figure 1), the search revealed a total of 84,950 articles, with three additional articles received from authors, four from reference lists, and 2,193 through the updated search in April 2020. After removing duplicates and screening abstracts for relevant inclusion criteria, data was extracted from 176 articles, and 113 were excluded with reasons. While 58 studies contained the appropriate methodological design to calculate Pearson product-moment correlations between executive functioning and subsequent acute stress, the association was reported only in 18 articles. Thirteen authors responded to our email requests and were considered for the meta-analysis (including five of whom had reported an association in their original articles). Overall, high heterogeneity in attentional measures was observed in the three corresponding studies. While these results were discussed in the qualitative synthesis, the high task diversity prevented us from merging them quantitatively into a coherent meta-analysis, leaving 10 studies for the latter. Our search additionally revealed five interventional studies investigating the role of executive functioning training upon stress regulation. The qualitative review separately discusses results from correlational and interventional designs.

3.2. Review of Correlational Studies

The complete set of data included 1,915 participants, with sample sizes ranging from 20 (Roelofs et al., 2007) to 360 (Mehta, 2012; see Table 2 for study characteristics). Most studies were peer-reviewed articles (80.77%). Grey literature was also included, with two master dissertations (Almeida, 2017; Fidler, 2006) and three PhD theses (Mehta, 2012; Morrison, 2014; Panganiban, 2013). Importantly, fifteen of the retained studies (57.69%) explicitly established the aim of investigating the predictive or moderating role of executive functioning in stress exposure, reactivity, and/or recovery, none of which initially intended to study executive function in relation to stress anticipation.

3.2.1. Quality Appraisal

All studies clearly reported the research question and defined and implemented valid and reliable measures of executive functioning and acute stress. Four studies did not report manipulation checks that would ensure the validity of their stressor. Most studies adequately defined the population inclusion and exclusion criteria (92.31%), although the majority did not report on the period during which the population was recruited (88.46%), did not provide the required information to calculate the eligible rate (92.31%), and failed to present a sample size justification (80.77%). In the original analyses, the majority of studies (72.22%) included sex as a covariate, but other important covariates (Laborde et al., 2017; Shields, 2020; Zänkert et al., 2019) such as medication intake (oral contraceptives included), smoking, specific menstrual cycle phases, and age were not systematically considered by authors. With respect to biomarker information, almost all studies (91.67%) adequately described assay methods, preservation, and storage. Only 52.63% detailed the quantitation methods, and 25% explained the reproducibility assessments. Where relevant, all studies failed to report whether the analyses were blinded for laboratory staff, and most did not report the laboratory in which the biomarker analyses were conducted. Only four studies fully reported information relative to biomarker distribution, outliers, and measurement inaccuracies.

3.2.2. Executive Functioning Facets Considered

The majority (76.92 %) of the studies investigated only one facet of executive functioning (see Table 2 for a summary of tasks and outcomes). Four studies included two different facets (Fiocco et al., 2007; Hendrawan et al., 2012; Mehta, 2012; Morrison, 2014), while two others measured three (Guevara & Murdock, 2019; Panganiban, 2013). The most represented facets were attentional control (*N*=9; Almeida, 2017; Fox et al., 2010; Iijima et al., 2018; McHugh et al., 2010; Morrison, 2014; Pilgrim et al., 2010; Roelofs et al., 2007; Sanchez et al., 2017; Schwerdtfeger & Derakshan, 2010), inhibition (*N*=9; Becker & Rohleder, 2020; Fidler, 2006; Guevara & Murdock, 2019; Hendrawan et al., 2012; Mehta, 2012; Morrison, 2014; Panganiban, 2013; Roos et al., 2017; Xin et al., 2019), and working memory (*N*=8; Almela et al., 2014; Becker & Rohleder, 2019; Fiocco et al., 2007; Goldfarb et al., 2017; Guevara & Murdock, 2019; LeMoult et al., 2019; Otto et al., 2013; Quaedflieg et al., 2019). Measures of flexibility (task-switching or verbal fluency) were considered in five studies (Fiocco et al., 2007; Guevara & Murdock, 2019; Hendrawan et al., 2012; Mehta, 2012; Panganiban, 2013) and updating in three (Lin et al., 2020; Panganiban, 2013; Quinn et al., 2019). There were no studies on planning.

3.2.3. Stressor Type and Severity

All but two studies measured stress in the laboratory, with 50% applying the moderate-high stressor TSST. Three employed a moderate variant by administering only the speech component (Fox et al., 2010; Sanchez et al., 2017; Schwerdtfeger & Derakshan, 2010). Additionally, one study used the moderate-high stressor of the Maastricht Acute Stress Test (MAST, Quaedflieg et al., 2019), two studies administered the moderate stressor of the SECPT (Becker & Rohleder, 2019, 2020), and three applied the moderate-low stressor CPT (Goldfarb et al., 2017; McHugh et al., 2010; Otto et al., 2013). In addition, two used a low severity stressor, the PASAT (Fidler, 2006; McHugh et al., 2010), while one implemented three cognitive tasks (Mehta, 2012). Seven studies included a control group in parallel to the stressor (Almeida, 2017; Becker & Rohleder, 2020; Otto et al., 2013; Panganiban, 2013; Quaedflieg et al., 2019; Quinn et al., 2019; Roos et al., 2017). Outside the laboratory, one study used an unmanned aerial vehicle simulation field stressor (Panganiban, 2013), and another studied daily stressors using ecological momentary assessment (Iijima et al., 2018).

3.2.4. Stress Phases and Outcomes

3.2.4.1. Exposure.

The systematic literature review found two studies (Iijima et al., 2018; Xin et al., 2019) investigating the role of executive functioning in exposure to stressful events.

3.2.4.2. Anticipation.

In the original papers, the anticipation phase was not considered by any author. Following the email requests, three relevant studies were identified. Fiocco and colleagues (2007) conceptualized anticipation as the change in cortisol between the pre-preparation and pre-speech phases of the TSST. Two studies computed the difference score between baseline heart rate (Roos et al., 2017) or HRV (HF-HRV, Roos et al., 2017; and RMSSD, Schwerdtfeger et al., 2010), and that of the TSST preparation phase.

3.2.4.3. Reactivity.

Reactivity was assessed across all 26 studies. Cortisol was the most frequent biomarker, with the majority of authors calculating the difference between baseline cortisol and peak (within article: Almeida, 2017; Goldfarb et al., 2017; LeMoult et al., 2019; McHugh et al., 2010; Quaedflieg et al., 2019; Xin et al., 2019; and provided by email: Becker & Rohleder, 2019, 2020; Fiocco et al., 2007; Guevera & Murdock, 2019; Xin et al., 2019), or post-stressor levels (Fox et al., 2010; Otto et al., 2013; Quinn et al., 2019). Some authors conceptualized cortisol reactivity as AUC_g (Fox et al., 2010), AUC_i (Almela et al., 2014; Pilgrim et al., 2010), or both (Guevara & Murdock, 2019). Others referred to the percentage change from baseline (Fiocco et al., 2007; Lin et al., 2020; Pilgrim et al., 2010; Roelofs et al., 2007), residual change score (Morrison, 2014), peak cortisol levels (Morrison, 2014), or average cortisol levels across the three recovery samples (Hendrawan et al., 2012).

Heart rate was measured in five studies, referred to as either change (Roos et al., 2017; Xin et al., 2019) or residual change (Fidler, 2006; Mehta, 2012) between baseline and average task levels, or average levels across the preparation, speech and arithmetic sections of the TSST (Hendrawan et al., 2012). HRV was also calculated in four studies, predominantly calculated as change between baseline and average task levels (HF-HRV and RMSSD, within article: Xin et al., 2019; RMSSD, Sanchez et al., 2017; and provided by email: Schwerdtfeger & Derakshan, 2010). One study also calculated the residual change score from baseline to average task levels (HF- and Low Frequency power HRV, LF-HRV, LF/HF ratio; Mehta, 2012).

The least represented outcomes were blood pressure, alpha-amylase, and skin conductance. Two research teams measured DBP and SBP, conveying the results as residual change score***s*** from baseline to task levels (Fidler, 2006; Mehta, 2012). Only two studies calculated the change between peak- and baseline salivary alpha-amylase, as provided by email (Becker & Rohleder, 2019, 2020), while one studied the average stressor skin conductance levels (Hendrawan et al., 2012).

Finally, subjective reactivity was measured alongside physiological measures in seven studies, with three studies incorporating a stress visual analog scale (VAS, Becker & Rohleder, 2019, 2020; Fiocco et al., 2007), and two studying feelings of tension (Almeida, 2017; Sanchez et al., 2017). Panganiban (2013) explored self-reported distress and Iijima and colleagues (2018) predicted tension-anxiety scores at the moment of a negative event.

3.2.4.4. Recovery.

Recovery was reported in 11 studies. Five investigated cortisol change (within article: LeMoult et al., 2019; and provided by email: Becker & Rohleder, 2019, 2020; Fiocco et al., 2007; Guevara & Murdock, 2019) or percentage change between peak levels and the last sample (Fiocco et al., 2007). Four studies provided data on HRV, using either change between the stressor and recovery period (within article: Sanchez et al., 2017; Schwerdtfeger & Derakshan, 2010; and provided by email: Schwerdtfeger & Derakshan, 2010; Xin et al., 2019), or residual change score by regressing baseline stress on immediate and delayed recovery periods (HF- and LF-HRV, LF/HF ratio; Mehta, 2012). An additional two provided change between peak and last samples for alpha-amylase (Becker & Rohleder, 2019, 2020). Lastly, two assessed pre- to post-stressor change in subjective stress (Becker & Rohleder, 2019, 2020), and one focused on tension-anxiety dynamics after a daily stressor (Iijima et al., 2018).

3.2.5. Results of Individual Correlational Studies by Stress Phase and Executive Functioning Facet

3.2.5.1. Exposure.

Participants with higher or lower inhibition abilities did not differ in terms of number of recent life events (Xin et al., 2019), while attentional bias towards negative material did not predict the frequency of daily negative events (Iijima et al., 2018).

3.2.5.2. Anticipation.

A negative and significant association was observed for attentional control (Schwerdtfeger & Derakshan, 2010), whereby longer times to disengage from angry faces predicted lower – and less healthy (see Kim et al., 2018; Shaffer & Ginsberg, 2017) – change in HF-HRV and RMSSD during stressor anticipation. Similarly, another study (Roos et al., 2017) reported a significant positive association between better baseline inhibition abilities and greater, more adaptive HRV increase in anticipation of the stressor. These results were not replicated for heart rate. Regarding cortisol, there were no significant associations with flexibility and working memory (Fiocco et al., 2007).

3.2.5.3. Reactivity.

3.2.5.3.1. Inhibition.

The association differs for cortisol, HRV, and subjective stress. With respect to cortisol, better inhibition abilities were associated with greater reactivity in both correlations (Xin et al., 2019) and hierarchical regression models (Morrison, 2014). In the latter, the interaction between inhibition and disengagement bias from threat was also significant, where greater difficulties disengaging from threat-related material, compared to neutral, predicted greater cortisol release in individuals with longer inhibition reaction times. For individuals with higher inhibition abilities, longer disengagement times from neutral materials was associated with greater cortisol reactivity.

In terms of HRV, two studies reported significant associations between inhibition and more adaptive HRV reactivity. In one study (Xin et al., 2019), lower – but not higher – inhibition abilities moderated the relationship between exposure to recent stressful events and smaller change in RMSSD and HF-HRV during the TSST, even when statistically controlling for both sex and neuroticism. The absence of findings for higher executive functioning was interpreted as resulting from these individuals' more effective coping abilities (i.e., flexible and adaptive appraisal of stressful life events) given a better performance of the prefrontal cortex. Similarly, better inhibition abilities predicted greater LF-HRV reactivity in a regression model (Mehta, 2012), but the result was no longer significant when applying Bonferroni corrections.

Finally, one study found that better inhibition scores predicted less subjective distress to a field stressor (Panganiban, 2013). Though a mediational model was not tested, better inhibition was also a negative predictor of task-related threat appraisal and feelings of uncontrollability, which could represent underlying mechanisms.

Overall, the absence of an association between inhibitory abilities and stress reactivity were otherwise reported in six studies, with respect to (a) cortisol (Becker & Rohleder, 2020; Guevara & Murdock, 2019; Hendrawan et al., 2012), (b) alpha-amylase, (Becker & Rohleder, 2020), (c) blood pressure (Fidler, 2006; Mehta, 2012), (d) heart rate and HRV (Fidler, 2006; Hendrawan et al., 2012; Roos et al., 2017), (e) skin conductance levels (Hendrawan et al., 2012), and (f) subjective stress (Becker & Rohleder, 2020).

3.2.5.3.2. Flexibility.

Associations for flexibility are scarce, emerging for skin conductance and cortisol only. In multiple linear regression models (Hendrawan et al., 2012), better verbal fluency was associated with less cortisol and skin conductance reactivity, although the latter association disappeared when body mass index (BMI) was controlled for. Better task-switching scores also significantly predicted skin conductance levels, over and above BMI. The authors postulated that executive functioning, dependent upon the frontal lobes, may allow individuals to efficiently integrate goal-related cues, organize and implement coping action plans, and continuously monitor and adjust behavior accordingly. The fact that the verbal fluency task may mobilize multiple cognitive facets in itself may explain its greater association with stress reactivity. In another study, better task-switching was associated with overall less cortisol output during the TSST (AUC_g), but not with increase (AUC_i; Guevara & Murdock, 2019). Task-switching did not predict AUC_i, with rumination, age, sex, education, and BMI as covariates, and simple bivariate correlations with cortisol change were not significant. Hence, while flexibility may not be associated with initial cortisol increase, it may be linked to less prolonged cortisol release over the session. Two studies replicated the absence of the association with both percentage increase and change in cortisol (Fiocco et al., 2007), as well as blood pressure and HRV (Mehta, 2012). With regards to subjective stress, flexibility was not associated with distress (Panganiban, 2013).

3.2.5.3.3. Working Memory Updating.

Three studies reported correlations with cortisol, subjective distress, and stress cytokines, respectively. First, Lin and colleagues (2020) identified longer 2-back reaction times as being significantly correlated with – and a predictor of – less cortisol reactivity. This was not replicated for 2-back accuracy or the 3-back task. The authors suggested that speed, but not performance, may be key in this association. Faster responders may be better able to mobilize their cognitive resources on a daily basis, leading to overall healthier – and more reactive – HPA responses. They further hypothesize that excessive task load in the 3-back level may have a role to play in the absence of an association.

Second, Panganiban (2013) found that updating significantly predicted greater subjective distress under low task load (i.e., less demanding stressor) in a hierarchical multiple regression model accounting for other cognitive facets. The researcher explains that individuals with greater updating abilities may be allocating their extra resources to stress processing, and that individuals should be trained to refocus these abilities upon task-relevant information instead.

Third and final, one research team (Quinn et al., 2019) reported the absence of bivariate correlations between updating and salivary interleukin-1β, interleukin-6, and tumor necrosis factor-α reactivity. In regression analyses controlling for gender and family income, updating did not significantly predict change, either.

3.2.5.3.4. Working Memory.

The results for working memory provide the clearest picture. Seven independent studies report no significant correlation between measures of working memory and cortisol (Becker & Rohleder, 2019; Fiocco et al., 2007; Goldfarb et al., 2017; Guevara & Murdock, 2019; LeMoult et al., 2019; Otto et al., 2013; Quaedflieg et al., 2019), alpha-amylase (Becker & Rohleder, 2019), and subjective stress reactivity (Becker & Rohleder, 2019).

Additionally, LeMoult and colleagues (2019) compared whether the association between working memory and cortisol reactivity and recovery differed between health individuals and patients with generalized anxiety disorder (GAD). Lower working memory was associated with a greater increase in cortisol reactivity in GAD patients only. The authors hypothesized that healthy individuals may be implementing efficient coping strategies and/or attenuating emotions faster than clinical populations, which would explain the findings.

One study (Almela et al., 2014) reported a curvilinear relationship between spatial working memory scores and cortisol AUC_i. They also find this effect for forward spatial length in women, and backward spatial length in men. They explain their findings for individuals with lower working memory on account of the effects of repeated stress upon cognitive functioning. When exposed to a threatening situation, an increase in cortisol is adaptive (i.e., Dickerson & Kemeny, 2004). The absence of a cortisol response in these individuals is indicative of the HPA-axis performing under optimal threshold. Repeated over time, this may lead to deteriorations of these individuals' executive functioning abilities. The lower response in individuals with better cognitive abilities was attributed to the fact that they may be generally less stressed by the cognitive nature of the TSST, given their higher abilities.

***3.2.5.3.5. Attention*.**

Overall, all but two studies (McHugh et al., 2010; Morrison, 2014) reported significant associations with respect to both early attentional biases and later voluntary control of attention. In terms of attentional biases, higher unaware bias towards negative material predicted greater cortisol reactivity to both a laboratory stressor and field-based examination stress, over and above state and trait anxiety, neuroticism and extraversion (Fox et al., 2010). Moreover, the same bias was positively correlated with overall cortisol release throughout these sessions. The other three attentional biases investigated were unrelated to either of these stress measures. Similarly, a moderating role of attentional biases and subjective stress was detected in Iijima and colleagues' (2018) study. Compared to individuals with low attentional bias towards negative material, those with higher scores presented greater increases in tension-anxious mood during a stressful event.

The results from these two studies suggest that preconscious bias towards negative cues may exacerbate subsequent subjective and physiological reactivity.

In another study, however, high responders – compared to low cortisol responders – presented stronger baseline *avoidant* attentional bias to threat (i.e., shorter RTs for angry vs. neutral faces; Roelofs et al., 2007). The authors highlight the importance of incorporating social threat-related material, as these findings were not replicated for happy or neutral material. Interestingly, cortisol responders presented high threat attentional bias *following* the TSST. The authors presume that the initial avoidant response may serve an adaptive function under rest conditions, as it limits excessive physiological arousal, but may fail under stress and lead to higher reactivity thereafter.

With respect to the voluntary control of attention, engagement and disengagement also seem to influence stress reactivity. Higher engagement towards stress-neutral words was significantly, negatively associated with cortisol AUC_i (Pilgrim et al., 2010), over and above the role of sex. Slower engagement was indicative of less cortisol increase, and further analyses revealed that individuals who, based on a median split, were slower to engage with stress-related stimuli presented a 3% *decrease* in response to the TSST, while fast engagers observed an increase of 81%. Given that the university sample in this study presumably had previous experience with speech-related activities, the authors interpreted the decrease in cortisol as habituation, an adaptive response. Rapid engagement of one's attention towards negative information, however, appears to magnify cortisol responsivity. Interestingly, the latter individuals also presented lower self-esteem, which could act as a moderator of this association.

Similarly, in one study (Sanchez et al., 2017), longer times to disengage from happy faces, and to engage with both disgust and sad stimuli were negatively associated with self-reported subjective tension in response to a stressor. In Schwerdtfeger and Derakshan's (2018) study, rapid disengagement from angry faces was similarly associated with – but also predicted, in a hierarchical model controlling for age, sex, caffeine and smoking – stronger decrease in HF-HRV during a speech task. In contrast, engagement towards angry or happy faces was unrelated to HRV. Although not tested, the authors suggested that this might be the result of individuals re-engaging their attention towards goal-specific information and invoking active coping strategies. The results from these two studies indicate that flexible disengagement of one's attention from threat-related stimuli and towards positive material may represent an important stress regulation strategy.

3.2.5.4. Recovery.

Across the 10 studies with measures of post-stressor recovery, four reported significant associations with executive functioning. One study (Xin et al., 2019) revealed a negative correlation with inhibition, so that higher performance was associated with slower cortisol recovery. In the same article, inhibition was not associated with heart rate or with HRV measures. In contrast, Mehta (2012) found that inhibition was a positive predictor of post-TSST immediate LF-HRV and HF-HRV recovery, along with delayed HF-HRV. Interestingly, findings from Fiocco and colleagues' (2007) study provided a statistical trend, where the association between verbal fluency and quicker cortisol recovery from the stressor approached significance. Another study (Sanchez et al., 2017) found that longer times to engage with disgust stimuli was associated with faster recovery from subjective tension. None of the other engagement and disengagement indices were correlated with neither subjective stress, or HRV.

3.2.6. Synthesis of Meta-Analysis

The databases contained six effect sizes (range: two to four per study; *N*=152) from two studies for anticipation, 28 effect sizes (range: one to six per study; *N*=499) from 10 studies for reactivity, and 24 effect sizes (range: two to six per study, *N*=410) from seven studies for recovery. Given that the anticipatory dataset comprised two studies and six outcomes, the RVE analyses suffered a lack of statistical power. As a result, anticipation was not further analyzed.

Similarly, due to low available degrees of freedom for the analyses, we were unable to calculate associations between cognitive flexibility and (a) cortisol (*number of studies, n=2*, *effect sizes*, *k*=3), SNS (*n*=0), and subjective reactivity (*n*=0), or with (b) cortisol (*n*=2, *k*=3), SNS (*n*=0), and subjective recovery (*n*= 0). For the same reasons, RVE analyses could not be run for the associations between inhibition and cortisol (*n*=3, *k*=4), SNS (*n*=3, *k*=7), and subjective reactivity (*n*=1, *k*=2), or with cortisol (*n*=3, *k*=4), SNS (*n*=2, *k*=5), and subjective recovery (*n*=1, *k*=2).

3.2.6.1. Working Memory.

There was as small, significant negative association between working memory and cortisol reactivity (*r*= -.09 *p*=.025, 95% CI [-0.15, -0.02]), indicating that better executive functioning was associated with less cortisol reactivity to the stressor. Heterogeneity was low, as I^2 and τ^2 both equaled 0.0. Sensitivity analyses indorsed the robustness of the results, as the model estimates remained unchanged with increasing or decreasing ρ values. The forest plot is presented in Figure 2. Applying Grubbs test failed to detect significant outliers, as did the outlier detection and influential case analyses on the aggregated dataset. Unfortunately, there were insufficient degrees of freedoms available for any of the planned moderator analyses. Additionally, there was a lack of available results for associations with cortisol recovery (*n*=5, *k=8),* as well as SNS and subjective stress reactivity (*k=1)* and recovery (*k*=1). This hindered the possibility of interpreting RVE analyses for these associations.

3.2.6.2. Publication Bias.

As the authors of grey literature (i.e., Master and PhD theses) did not provide correlations following our email requests, they were not incorporated into the meta-analysis. Funnel plot analysis for the working memory and cortisol reactivity database showed that all studies were dispersed symmetrically around the pooled effect size within the funnel itself. None of the effect sizes were found in regions of statistical significance (in grey) in the contour-enhanced funnel plots for working memory (Figure 3). Egger's test (Egger et al., 1997), which tests the null hypothesis that the funnel plot is asymmetric, further confirmed the absence of bias (z= -0.16, p=.832). The trim-and-fill analyses revealed that no modifications (i.e., additions or subtractions of studies) needed to be made. Hence, given these statistical findings, and that authors provided specific correlations tailored to our research questions, it is unlikely that the findings emerge from a potential publication bias.

3.3. Review of Interventional Studies

The search revealed five interventional studies for stress regulation, with four targeting attentional control (Baert et al., 2012; Higgins & Hughes, 2012; Pilgrim et al., 2014, 2017), and one (Quinn et al., 2014) focused upon updating. Four are peer-reviewed articles, and one (Pilgrim et al., 2017) is an unpublished article (see Table 3 for further study characteristics).

3.3.1. Risk of Bias

Overall, four interventional studies reported some concerns of bias, while one was rated as having high risk. All but one study presented concerns regarding the randomization process, as few reported the way in which this was done. One study (Pilgrim et al., 2014) reported high risk for the randomization process, with training groups presenting significant differences in depression symptoms at baseline. There are some concerns regarding deviations from the intended interventions, but outcome data was available for all participants, and the risk of bias for outcome measurement was low across all studies. Although we lacked the evidence to claim the studies did not report expected analyses, a plan of intended analyses was missing for all studies. With respect to biomarker analysis, all studies appropriately reported specimen characteristic and assay methods where relevant, although information regarding blinded analyses and reproducibility assessments were missing in one study, quantitation methods in a second, and quality control and blinded analysis in a third. All five studies did not report complete information regarding distribution of biomarker data.

3.3.2. Intervention Format

The attentional training paradigms were based either on the Dot-Probe Task (Baert et al., 2012; Higgins & Hughes, 2012; Pilgrim et al., 2017) or on Spatial Cueing Attentional Bias Modification (ABM; Pilgrim et al., 2014, 2017). Pilgrim and colleagues (2017) compared the effects of these two paradigms. With respect to updating, Quinn and colleagues (2014) administered affective and non-affective versions of the N-Back Task. All interventions included emotional material and comprised at least one active control group, while two incorporated an additional passive control group (Pilgrim et al., 2014; 2017).

All training programs were individualized and computerized. Two interventions required participants to complete the tasks from home, either online (Baert et al., 2012) or on a provided laptop (Pilgrim et al., 2017). The remainder required access to the university laboratory. The number of sessions ranged from one (Higgins & Hughes, 2012; Quinn et al., 2014) to six (Baert et al., 2012), with an average of 3.20. Interventions comprising several sessions all occurred on consecutive days. The length of each training sessions ranged from 19 (Higgins & Hughes, 2012) to 45 minutes (Pilgrim et al., 2014, 2017).

3.3.3. Stressor Type and Severity

Homogeneity was observed in the stressors used to elicit either stress in the laboratory. Three studies (Pilgrim et al., 2014, 2017; Quinn et al., 2014) applied the moderate-high severity socio-evaluative TSST. In two moderate-severity variations, Higgins & Hughes (2012) asked participants to give a six-minute speech from a set of 28 words, while Baert and colleagues (2012) conducted a mock interview a week ahead of the participants' actual job interview.

3.3.4. Stress Phases and Outcomes

3.3.4.1. Reactivity.

All five studies investigated stress reactivity but showed heterogeneity in its assessment. The majority (80%) reported only physiological measures, whereas one study reported both physiological and subjective indicators ("tense" VAS; Baert et al., 2012). Most studies (60%) included repeated measurement of salivary cortisol across the stressor. Of these, one study conceptualized reactivity as AUC_i (Pilgrim et al., 2017), another as both AUC_g and AUC_i (Pilgrim et al., 2014), and a third (Quinn et al., 2014) as the difference between baseline and post-TSST. In addition to cortisol, one study calculated salivary alpha-amylase (sAA) AUC_g and AUC_i (Pilgrim et al., 2014). Baert and colleagues (2012) measured HRV (RMSSD, LF, HF, LF/HF ratio), comparing baseline HRV with levels during the preparation and speech (Baert et al., 2012). Finally, Higgins and Hughes (2012) assessed mean stressor DBP, SBP, and heart rate.

3.3.4.2. Recovery.

Only two (40%) studies investigated the recovery phase following a stressor. Baert and colleagues (2012) calculated HRV return to baseline, comparing the HRV values during the post-stressor recovery phases to baseline HRV values, while Higgins and Hughes (2012) conceptualized recovery as mean DBP, SBP, and heart rate levels post-stressor.

3.3.4.3. Habituation.

Pilgrim and colleagues (2017) administered the TSST twice, at a two-month interval, thereby qualifying as the only study in this systematic literature review explicitly assessing habituation.

3.3.5. Results of Individual Interventional Studies by Stress Phase and Executive Functioning Facet

3.3.5.1. Reactivity.

Pilgrim and colleagues (2014) found that, when controlling for sex and oral contraceptives, participants in the masked and supraliminal groups showed higher cortisol increase (AUC_i) – but not overall cortisol output (AUC_g) – compared to controls. Contrary to expectations, individuals in the supraliminal training (with full conscious awareness of the stimulus) also presented overall higher sAA AUC_i and AUC_g compared to both masked (limited conscious awareness of the stimulus) and controls. Similarly, individuals in the spatial cueing training and gender identification control group in Pilgrim and colleagues' (2017) study also presented higher cortisol AUC_i to the first TSST, compared to the passive control condition and when controlling for sex. This was not the case for the Dot-Probe ABM. Synonyms of poor stress regulation, these findings are contradictory. The authors identified several limitations to the spatial cueing paradigm implemented that could explain this. In addition, they suggested that while attentional training may be successful in reducing stress reactivity in individuals suffering from clinical disorders, this may not be the case of healthy populations.

Furthermore, a hierarchical multiple regression model in Pilgrim and colleagues' (2014) research revealed that baseline attentional control moderated the relationship between Spatial Cueing training and reactivity, whereby the intervention increased cortisol levels in individuals with higher baseline attentional control only. The authors reference the dual system perspective on information processing (e.g. Ouimet et al., 2009). Threat processing involves two steps, the first of which includes a rapid, automatic associative network, followed by a slower, reflective system. Given that individuals with high attentional control are thought to prioritize rule-based processes to govern stress responses, it is plausible that the intervention trained the associative system, leaving the rule-based system – and the subsequent stress response for these individuals – intact. This moderator effect was not replicated in their more recent study (Pilgrim et al., 2017), demonstrating the need for further research to test this theory.

Baert and colleagues' (2012) findings report no main effect of attentional training upon self-reported tension or HRV. While Higgins and Hughes (2012) replicated these findings for DBP, SBP, and heart rate, they did find a significant interaction between time, intervention group, and neuroticism for SBP. In the anti-negative group, participants high on neuroticism showed normal SBP responses, while those low on neuroticism showed excessive reactivity to the stressor. The opposite pattern was true for the control training, during which a bias *towards* negative material was induced. Individuals low on neuroticism may have less exposure to events perceived as stressful and, consequently, less practice in optimal strategy choosing. Avoiding stress-related cues during the anti-negative training may have led to subsequent poor coping implementation and, ultimately, to an exaggerated stress response to the impending stressor.

Beyond these results for attentional training, there was no main effect of updating training on cortisol reactivity in Quinn and colleagues' (2014) study. They do report, however, a significant interaction between intervention group and ruminative tendencies. Relative to participants in the control group, individuals with *higher* – but not lower – ruminative tendencies in the training group benefited from lower cortisol reactivity to the stressor.

3.3.5.2. Recovery.

In one study (Baert et al., 2012), executive functioning training provided more promising results for recovery. A significant increase in RMSSD during recovery was observed for the training group only, indicating faster return to baseline. In the control group, relative to the training group, the LF/HF ratio and LF units increased post-stressor, while the HF units decreased. While the stress response returned to baseline in the intervention group, it pursued its increase in controls. These findings reveal that attention training promoted stress recovery.

3.3.5.3. Habituation.

Pilgrim and colleagues (2017) found that participants in both trainings presented lower cortisol reactivity to the second TSST compared to those in the passive control group, even when controlling for sex. A hierarchical multiple regression model predicting cortisol change from TSST 1 to 2 indicated a statistical trend towards an interaction between baseline voluntary attention and training group. Simple slope analyses showed that participants with *low* – but not high – baseline voluntary attention, in both training groups, presented significantly less cortisol reactivity compared to the two control groups. These emerging findings highlight the potential for long-term effects of the ABM paradigms and point to the requirement of accounting for baseline attentional capacity when planning interventions.

3.4. The Role of Chronological Age

Regarding our third research question on the role of age, mean age ranged from 18.04 (*SD*=0.20; Morrison, 2014) to 63.54 years (*SD*=3.66; Almela et al., 2014) for correlational studies. Only two interventional studies reported overall average age, ranging from 20.34 (3.39; Higgins & Hughes, 2012) to 26.70 (*SD*=6.60; Baert et al., 2012). Only three studies (Almela et al., 2014; Fiocco et al., 2007; Guevara & Murdock, 2019) included older adults (i.e., > 60 years old) within their samples. While some controlled for age in their statistical analyses, none of these authors included a research question regarding the moderating role of age.

4. Discussion

This systematic literature review and meta-analysis is the first to evaluate the extent to which executive functioning represents a protective factor for acute stress responses with respect to anticipation, exposure, reactivity, recovery, and habituation in healthy adults. Integrating findings from correlational and interventional designs, we examined three specific pre-registered goals, namely to (a) identify the precise executive functioning facets involved in this association, (b) differentiate the stress phases and measures influenced by executive functioning, and (c) evaluate the extent to which the relationship varies with increasing age.

4.1. Answers from Correlational Studies

4.1.1. Systematic Literature Review

The search for correlational studies not only revealed that only 57.69% of studies explicitly aimed to explore the protective role of executive functioning for stress regulation, 76.92% of them investigated only one facet of executive functioning. As a result, deriving a clear-cut conclusion on the distinctive roles of different facets is currently limited by the paucity of available research. Moreover, 72.22% included sex as a covariate, but other exclusion criteria (e.g., smoking, medication use) or relevant covariates (e.g., age testing time of day) were not consistent across studies. Their results must be interpreted in light of these limitations. The current review nonetheless confirmed significant associations between executive functioning and acute stress responses.

While no significant associations were reported for stress exposure, two of the three studies measuring anticipation provided significant correlations. Better inhibition abilities (Roos et al., 2017) and less time to disengage from angry faces (Schwerdtfeger & Derakshan, 2010) were associated with greater anticipatory HRV responses, indicative of a more adaptive response. As the effect did not extend to cortisol, the regulative role of executive functioning may be limited to associations with healthier anticipatory responses of the sympathetic and parasympathetic systems.

Reactivity was the predominant phase taken into consideration by researchers. Attentional control emerged as the most frequently associated facet, where both unaware bias towards – and faster engagement with – negative material were associated with exaggerated cortisol reactivity (Fox et al., 2010; Pilgrim et al., 2010) and greater subjective stress in response to a stressor (Iijima et al., 2018; Sanchez et al., 2017). Faster disengagement times from threat-related material led to a more adaptive, pronounced HRV response (Schwerdtfeger et al., 2010), while longer disengagement times from positive material was associated with lower subjective tension in response to the stressor (Sanchez et al., 2017). Hence, pre-conscious attentional biases towards threat-related cues may enhance the initial cortisol response, while the more voluntary control of attention away from negative information, and towards positive material, may lead to more adaptive stress responses.

Associations for other facets were limited. First, inhibition was unrelated to stress reactivity in 66.67% of the studies. When a significant correlation emerged, however, higher inhibition was associated with a more healthy, responsive HRV activity to a stressor (Roos et al., 2017; Xin et al., 2019), less subjective distress (Panganiban, 2013), and higher cortisol reactivity (Xin et al., 2019). It also moderated the relationship between attentional disengagement and subsequent cortisol reactivity. More specifically, disengagement from negative material predicted cortisol reactivity in individuals with lower inhibitory control, while neutral material was more predictive for those with higher executive functioning. Second, only two of five studies on flexibility reported significant associations, where better flexibility performance was associated with less skin conductance (Hendrawan et al., 2012) and less overall cortisol output (Guevara & Murdock, 2019). Third, two of three studies on working memory updating also reported significant correlations, where better ability was associated with less cortisol reactivity (Lin et al., 2020) and, surprisingly, higher subjective stress (Panganiban, 2013). The findings were not replicated for cytokines (Quinn et al., 2019). Finally, only one of seven studies on working memory reported a significant, curvilinear association with cortisol reactivity. Given these observations, attentional control may be particularly relevant for stress regulation, while the other emerging associations require further replication.

In terms of recovery, 36.36% of studies reported significant associations. Both better inhibition and longer engagement with disgust-related stimuli appeared to promote faster vagal (Mehta, 2012) and subjective (Sanchez et al., 2017) recovery from stress, but inhibition was also associated with slower cortisol recovery (Xin et al., 2019). Although these emerging results indicate the presence of an association between executive functioning and recovery, it seems complicated, at this stage, to conclude the facet and stress outcome to which it pertains.

4.1.2. Meta-Analysis

Attributable to limited available data for other associations, the meta-analysis focused on working memory and cortisol. Interestingly, while each independent study did not report significant correlations in their original article, their combination within a meta-analysis revealed a small, but significant, negative association. Better working memory at baseline was associated with lower subsequent cortisol change to the acute stressor.

Research on stress and health has brought to light that stress reactivity is a normative process spread across a continuum. Both blunted and excessively high reactivity are associated with unhealthy behaviors, negative health outcomes, and disease (e.g., Lovallo, 2011; Phillips et al., 2013). For example, the cumulative effect of sustained repetitive activation and adaptation of physiological systems in response to stressors ultimately leads to their wear-and-tear and, subsequently, to long-term health problems (i.e., allostatic load, McEwen, 1998). A moderate reaction to stress is therefore considered the most adaptive (Lovallo, 2013). The current meta-analysis indicates that higher executive functioning may limit excessive cortisol release, potentially preventing physiological dysregulation and reducing the risk of poor health.

4.2. Answers from Interventional Studies

Similar to correlational studies, a distinctive finding of this review is the lack of interventions targeting multiple facets of executive functioning, in addition to the fact that the facets targeted by trainings were limited to attentional control and updating. With respect to the risk of bias, only one study presented a high risk, due to significant differences in depressive symptomatology between the groups. The remaining studies presented some risk of bias, demonstrating the need for interventional studies to detail pre-registered data analyses plans and to provide more complete descriptions of biomarker analyses.

Based on the four studies available on the former, attentional training does not appear to have a positive impact upon stress reactivity. In two studies (Pilgrim et al., 2014; 2017), heightened immediate reactivity to laboratory stressors was noted following spatial cueing ABM, attributable to the task itself. With respect to heart rate and blood pressure, a lack of effect of attentional training was observed (Baert et al., 2012; Higgins & Hughes, 2012). Higgins and Hughes (2012) reported a negative impact of anti-negative attentional training. However, interesting findings were noted for updating. Compared to the control group, individuals following a working memory updating training displayed significant reductions in cortisol reactivity if they presented high – but not low – ruminative tendencies (Quinn et al., 2014). With respect to recovery, one (Baert et al., 2012) of the two studies reported that Dot-Probe ABM training promoted faster – and thereby, more adaptive – HRV *recovery* following a stressor.

Converging with findings from correlational studies, training individuals to modify their attentional focus away from threatening material, and towards positive information, may therefore play an important role for homeostasis. Attentional processes may not only be implicated in modulating initial heart rate activation to a stressor, but also in regulating physiological return to baseline and limiting sustained, maladaptive activation. Correspondingly, Dot-Probe and Spatial Cueing ABM training, relative to the control group, were associated with lower cortisol reactivity to a second TSST administered two months later. This finding was enhanced in individuals presenting lower attentional control at baseline (Pilgrim et al., 2017). ABM offers promising long-term effects for habituation to repeated stressors, prompting the need for future interventions to account for larger study timeframes.

4.3. Age-related, Cognitive and Behavioral Mediators and Moderators of the Association

Our last research question relating to the moderating role of age was not answered for two reasons. First, none of the studies included in the qualitative synthesis addressed the moderating role of age per se, with only three including older adults in their sample. Second, the lack of statistical power in the meta-analysis precluded us from running moderator analyses. Given the existence of lifespan changes in both stress regulation and executive functioning, examining the influential role of age remains an important new research avenue.

However, the qualitative synthesis did reveal the existence of other mediators and moderators. In one study, lower self-esteem was present in individuals who displayed an attentional bias towards negative material, as well as subsequent exacerbated cortisol reactivity to a stressor (Pilgrim et al., 2010). In another study (Panganiban, 2013), better inhibition negatively predicted threat appraisal and stress uncontrollability, while the opposite was surprisingly true for updating. Although the contrasting results require further study, they allow to bridge existing knowledge on executive functioning with traditional theories of appraisal and coping (Lazarus & Folkman, 1984).

Multiple authors also advocated coping implementation as a mechanism. For example, Higgins and Hughes (2012) revealed that training individuals, who were lower on neuroticism, to displace their attention away from negative material led to an *exaggerated* stress response to the stressor, and sustained activation after its termination. They explain their findings on the lack of coping strategies implemented. Similarly, LeMoult and colleagues (2019) also corroborated this coping-deficit theory in their research, where better working memory was associated with less reactivity in clinically anxious individuals but not in healthy control. Finally, noticing that lower – but not higher – executive functioning mediated the relationship between stressful life events and HRV acute stress responses, Xin and colleagues (2019) postulated that individuals with higher inhibition abilities might apply more efficient coping strategies. In line with this interpretation, recent research (e.g., Nieto et al., 2019) indicates that individuals with better inhibition abilities were less likely to resort to avoidant coping. Given that the latter is known to activate excessive stressor responses, executive functioning could serve as a protective factor.

Similarly, Quinn and colleagues (2014) emphasized the moderating role of rumination, whereby their updating training was beneficial in reducing cortisol reactivity in individuals who presented a greater tendency to ruminate. These findings are in line with research indicating that stress responses may depend on the personal abilities to inhibit negative thoughts and worries before or after a stressor. For example, the degree of thought intrusion following a thought suppression task is lower if the individual presents better working memory (e.g., Brewin & Beaton, 2002). Similarly, executive functioning has been reported to moderate the association between a stressful event and subsequent rumination tendencies (De Lissnyder et al., 2012). In turn, rumination is known to prolong physiological stress responses (Brosschot et al., 2006).

4.4. Limitations

A notable finding of this work is the lack of existing studies focused specifically on the association between executive functioning and stress responses. In addition, sufficient data to perform a meta-analysis was only available for working memory. This lack of statistical power for RVE analyses prevented us from carrying out supplementary moderator analyses, including for age. Moreover, we were unable to control for important confounding variables such as sex, medication use, smoking, stressor type and severity, or testing time of day.

Nonetheless, the meta-analysis showed very low heterogeneity and did not suffer from publication bias. As a result, the association between working memory and both cortisol reactivity appears valid. It is important to note, nonetheless, that although the design of these studies allows for the examination of executive functioning as a predictor of acute stress, these results remain correlational in nature. The combination of both correlational and interventional findings in the current qualitative review contributes greater weight to shining the light on the current association of interest.

4.5. Implications and Future Perspectives

In the area of executive functioning and stress regulation, this review has clarified that further research is warranted. Future studies must implement the appropriate design to allow for the determination of causality of this relationship. This implies using an appropriate timeframe between the evaluation of executive functioning and the administration of an acute stressor. Ideally, using longitudinal and executive functioning interventional designs would enable the causality of this association to be established. While attentional training appears to have been prioritized thus far, researchers must also consider a greater variety of executive functioning facets to allow for a more fine-grained understanding of the role of each particular function. In the same vein, research teams must consider both subjective and physiological outcome measures. Moreover, our conclusions limited to health adults, future studies could focus on comparing these results among clinical populations. Finally, the next research endeavors should consider the role of age-related, cognitive, and behavioral mediators and moderators. The findings highlight the necessity to explore not only the stress regulation strategies that may be indirectly targeted by executive functioning training, but other major variables relevant to the field that were not systematically reported or investigated to this day. Among potential candidates, age, sex, rumination, and coping strategies must be at the forefront of future studies.

Although scarce at the current moment, the emerging results reveal this avenue of research as particularly promising.

Lastly, the current review holds several implications for future perspectives in healthy individuals. The qualitative and quantitative review identified attentional control and working memory, respectively, as prominent candidates for interventions. Cognitive control training techniques are already implemented in specific therapies, such as Wells and Matthews' (1996) metacognitive therapy for anxiety and depression. Should future research replicate the emerging associations for other facets in community-dwelling populations, health prevention campaigns could propose such trainings to enable individuals to regulate their daily stress more efficiently. Limiting repeated – and often unnecessary – stress activation to daily events would prevent both the cumulative, deleterious effects of allostatic load and its associated health issues.

5. Conclusion

The results of the current systematic literature review and meta-analysis identified significant relationships between executive functioning and four of the five phases of acute stress, namely anticipation, reactivity, recovery, and habituation. Better attentional control was recurrently identified as being associated with better reactivity and recovery. The meta-analysis of 10 studies also revealed working memory as being significantly associated with less cortisol reactivity in response to an acute stressor. These findings suggest a regulative role of executive functioning for promoting healthier stress responses. Future research combining greater diversification in executive functioning facets, physiological and subjective stress outcomes, and mediating and moderating mechanisms are required to fully comprehend the precise role played by executive functioning with respect to the stress response.

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7. Figure Captions

Figure 1: PRISMA Flow Diagram

A flow diagram of the search and selection process.

Figure 2: Forest Plot of the Correlations between Working Memory and Cortisol Reactivity

Forest plot presenting individual correlations and respective study weight, as well as overall effect size following the robust variation estimation meta-analysis conducted for working memory and cortisol reactivity to an acute stressor.

Figure 3: Contour-enhanced Funnel Plot investigating Publication Bias on the Aggregated Reactivity Data

The funnel plot confirms the absence of publication bias, as none of the studies fall within the regions of statistical significance. The unshaded, dark gray, medium gray, and light gray correspond to p-values ranging above .10, between .10 and .05, between .05 and .01, and below .01, respectively.

8. Tables

Table 1

Definitions of Stress Phases Investigated in the Systematic Literature Review and Meta-Analysis

	Anticipation	Exposure	Reactivity	Recovery	Habituation
Cortisol and alpha-amylase	Change from the moment of stressor instructions to start of stressor		Change from pre-stressor values to peak values	Change from peak values to last measure obtained during the session	Comparison of reactivity and recovery levels when confronted to repeated or similar stressors
Heart rate and blood pressure	Change from the moment of stressor instructions to levels during instructions period		Change from pre-stressor values to average levels during stressor	Change from average levels during stressor to last measure obtained	
Self-reported measures	Change from the moment of stressor instructions to start of stressor	Confrontation with an event perceived as stressful or threatening	Change from immediate pre- to post-stressor levels	Change from immediate post-stressor levels to last measure obtained	

Table 2

Characteristics of the Studies included in the Systematic Literature Review and Meta-Analysis

Study	Sample	Executive Functioning Facets and Tasks	Acute Stressor	Stress Phases and Outcomes	Findings
Almeida (2017)	*N*=80; M_{age}= 18.85 (1.54); 58.75% female	Attention: Performance score on Multiple Object Tracking	Laboratory: TSST (*N*=56) vs. informational travel video in the laboratory (*N*=24)	Reactivity • Salivary cortisol: PEAK – BASELINE • Subjective: Post-TSST tension (Brunel Mood Scale)	Pearson product-moment correlations: baseline 5-targets MOT performance negatively correlated with post-TSST tension ($r(79)$ = -.25, p=.027); Correlations between baseline EF and cortisol change due to stressor not reported
Almela et al., (2014)	*N*=65; $M_{age\ women}$= 63.54 (3.66); $M_{age\ men}$= 63.29 (5.21); 53.85% female	Working memory: Spatial span score and errors on the spatial working memory	Laboratory: TSST	Reactivity • Salivary cortisol: AUC_i • Heart rate: did not report the outcome	Regression analyses: curvilinear relationship between cortisol AUC_i and (a) spatial working memory across all participants (AdjR^2= .19, ΔR^2= .07, β=−.29, $F(1,54)$= 5.13, p= .028); (b) forward spatial length in women (AdjR^2= .18, ΔR^2 = .06, $F_{(1,52)}$= 4.12, p=.048, men: β=.09, p> .05, women: β=.698, p= .013); and (c) backward spatial length in men (AdjR^2=.09, $\Delta R2$=.09, $F(1,52)$= 5.97, p=.018, men: β=.38, p= .016, women: β=−.396,p> .1); covariate: sex
Becker & Rohleder, (2019)*	*N*=33; M_{age}= 24.00 (5.70); 75.75% female	Working memory: Sum of correctly recalled words from the last three words on the Word List Task	Laboratory: SECPT	*Obtained by email:* Reactivity: • Cortisol and AA: PEAK – POST-EF • Subjective VAS: PRE-SECPT –POST-SECPT Recovery: • Cortisol and AA: LAST – PEAK • Subjective VAS: LAST – POST-SECPT	Pearson product-moment correlations: non-significant association between working memory and both reactivity and recovery

Table 2 (continued).

Study	Sample	Executive Functioning Facets and Tasks	Acute Stressor	Stress Phases and Outcomes	Findings
Becker & Rohleder, (2020)*	*N*=81; M_{age}= 21.80 (3.90); 69.14% female	Inhibition: RT and number of errors on Stroop Color-Word Test	Laboratory: SECPT (*N*=69) vs. warm-water control group (*N*=12)	*Obtained by email*: Reactivity: • Salivary cortisol and AA: PEAK – POST-EF • Subjective VAS: PRE-SECPT – POST-SECPT Recovery: • Salivary cortisol and AA: LAST – PEAK • Subjective VAS: LAST – POST-SECPT	Pearson product-moment correlations: non-significant association between baseline inhibition and both reactivity or recovery for individuals who underwent the stressor
Fidler (2006)	*N*=98; M_{age} = 24.63 (3.78); 48.98% female	Inhibition: Interference score on Stroop Color and Word Task	Laboratory: controllable and uncontrollable versions of the PASAT	Reactivity: • DBP, SBP and HR: residual score obtained by regressing mean stress responses on respective baseline mean	Correlations: non-significant associations between baseline Stroop interference score and stress reactivity
Fiocco et al., (2007)	*N*=101; M_{age} = 58.03 (0.42 standard error); 78.22% female	Cognitive flexibility: Phonetic and Category Fluency total score Working memory: Forward and Reverse Digit Span scores	Laboratory: TSST	*Obtained within article:* Reactivity: • Salivary cortisol: percentage increase [(5MIN POST-TSST –BASELINE)/ BASELINE] • Subjective: post-stressor stress Recovery: • Salivary cortisol: percentage change [(45MIN POST-TSST –15MIN POST-TSST)/15MIN POST-TSST] *Obtained by email:* Anticipation: • Salivary cortisol: PRE-TSST – PRE-ANTICIPATION Reactivity: • Salivary cortisol: PEAK – PRE-TSST Recovery: • Salivary cortisol: LAST – PEAK	Bivariate correlations (within article): non-significant associations between baseline EF and both reactivity and recovery Pearson product-moment (obtained by email): no significant associations. Category fluency approached significance with quicker cortisol recovery (*r*(101)=.19, *p*=.054)

Table 2 (continued).

Study	Sample	Executive Functioning Facets and Tasks	Acute Stressor	Stress Phases and Outcomes	Findings
Fox et al., (2010)	Original *N*=104; M_{age} = 21.80 (2.90); 0% female; 4 months post-baseline: Laboratory stressor, *N*=82; 8 months post-baseline: Field stressor, *N*=70	Attention: Aware and unaware positive and negative bias scores on the pictorial Visual Probe Task	Laboratory stressor: five-minute socially-evaluated speech on the need of statistics Examination stressor: "have I prepared well enough for my exams?"	Reactivity: • Salivary cortisol: AUC_g ; change = 5MIN POST-TSST – BASELINE;	Pearson correlations: masked negative bias significantly correlated with AUC_g ($r(80)= .43$, $p<.001$) to laboratory stressor, and to cortisol AUC_g ($r(68)= .48$, $p<.001$) to examination stressor Multiple regression analyses: Same bias predicted change in cortisol to laboratory stressor (β=.45, t(82)=3.70, $p<.001$) and to examination stress (β=.49, $t(70)$=4.0, $p<.001$); covariates: neuroticism, extraversion, trait and state anxiety, and BDI-II
Goldfarb et al., (2017)*	*N*=38 in original study, *N*=18 for meta-analysis; M_{age}= 22.11 (3.36); 44.44 % female	Working memory: Listening Span score	Laboratory: random assignment to CPT (*N*=20) or warm-water control (*N*=18) session first	*Obtained by email :* Reactivity: • Salivary cortisol: POST-CPT – POST-LSPAN	Pearson product-moment correlations: no significant associations for participants who underwent control condition first (*N*=18)
Guevara & Murdock (2019)*	*N*=71; M_{age}= 60.62 (6.19); 74.65% female	Cognitive flexibility: Perseverative responses and errors, and non-perseverative errors on WCST) Inhibition: Z-score (Time and number of errors on Color-Word Test from Delis-Kaplan EF System Working memory: Total number of correct responses and largest number of digits correctly on Forward Digit Span Task	Laboratory: TSST	*Obtained within article:* Reactivity: • Salivary cortisol: AUC_g and AUC_i *Obtained by email:* Reactivity: • Salivary cortisol: PEAK – POST-EF Recovery: • Salivary cortisol: LAST – PEAK	Pearson product-moment correlations: better cognitive flexibility associated with less AUC_g ($r(71)$= -.28, $p<.05$) Linear regression model: cognitive flexibility did not predict AUC_i ; covariates: age, sex, education level, and BMI Mediation model: lack of indirect effect via ruminations; covariates: age, sex, education level, and BMI Pearson product-moment correlations (obtained by email): no significant associations

Table 2 (continued).

Study	**Sample**	**Executive Functioning Facets and Tasks**	**Acute Stressor**	**Stress Phases and Outcomes**	**Findings**
Hendrawan et al., (2012)	*N*=32; M_{age}= 19.13 (1.00); 0% female	Cognitive flexibility: Total number of words generated from the Letter Fluency Test; Number of categories completed on the WCST Inhibition: RT on the third trial of the Stroop Word-Color Task	Laboratory: TSST	Reactivity: • Salivary cortisol: Average cortisol levels across the three recovery samples • HR and SCL: Average levels across the preparation, speech and mental arithmetic sections.	Multiple regression model: letter fluency negatively associated with SCL (R^2=.31, β=−.42, p<.05) and cortisol (R^2 = .20, β = -.49, p<.05). Only the latter stayed significant when adjusting for BMI Pearson product-moment correlations: WCST negatively correlated with SCL (R^2=.31, β=-.42, p<.05)
Iijima et al., (2018)	*N*=48; M_{age}= 19.70 (1.0); 45.83% female	Attention Negative Attentional Bias Score on Dot-Probe Task	Daily stressors over six consecutive days	Exposure: • Occurrence of a negative event Reactivity: • Predicting tension-anxiety (Profile of Mood States-Brief Version) at time of stressor by negative event Recovery • Predicting post-stressor tension-anxiety by the negative event	Multi-level analyses: attentional bias moderated reactivity but not recovery. Compared to individuals with lower bias scores, those with higher scores (*B*=2.25, *SE*=0.33, *t*=6.76, p<.001) showed greater increase in stress-anxious mood during stressful event; covariates: gender, STAI, and current activity pleasantness Multiple regression analyses: attentional bias did not predict the frequency of negative events
LeMoult et al., (2019)*	*N*=30 healthy individuals vs. 22 patients; M_{age}= 29.27 (10.34); 60% female	Working memory Negative and Neutral Reading Spans scores	Laboratory: TSST	*Obtained within article and by email:* Reactivity: • Salivary cortisol: PEAK – BASELINE Recovery: • Salivary cortisol: LAST – PEAK	Multi-level analyses and Pearson product-moment correlations: no significant associations between reading spans and both cortisol reactivity and recovery; no covariates as they were not predictive of cortisol response

Table 2 (continued).

Study	Sample	Executive Functioning Facets and Tasks	Acute Stressor	Stress Phases and Outcomes	Findings
Lin et al., (2020)	*N*=39; M_{age}= 21.92 (2.08); 0% female	Updating: Accuracy and RT on 2- and 3-back Task	Laboratory: TSST	Reactivity: • Salivary cortisol: percentage increase [(PEAK – BASELINE)/BASELINE]	Bivariate correlations: significant association between 2-back RT and reactivity ($r(39)$= -.37, p=.020). Hierarchical regression model: 2-back RT significantly predicted reactivity (β= -.38, t= -2.18, p=.037); covariates: age and neuroticism
McHugh et al., (2010)	Study 1: *N*=35; M_{age}= 21.90 (4.60); 51.43% female Study 2: *N*=65; M_{age}= 23.80 (7.70); 52.31% female	Attention: Threat attentional bias on Dot-Probe Task	Laboratory: PASAT (study 1) and CPT (study 2)	*Obtained by email:* Reactivity • Salivary cortisol: POST-STRESS – POST-EF	Pearson product-moment correlations: no significant associations in either study
Mehta (2012)	*N*=360 adults M_{age} not reported 50.00% female	Inhibition: Interference RT on Stroop Color-Word Test Cognitive Flexibility: Trail Making Test B/A ratio	Laboratory: Stressor composed of Stroop interference, memory, and tracking tasks	Reactivity: • DBP, SBP, HR, HRV (LF-HRV, HF-HRV, LF/HF ratio): residual change score from baseline to average levels across three tasks Recovery: • DBP, SBP, HR, HRV (LF-HRV, HF-HRV, LF/HF ratio): residual change score from baseline to average recovery levels	Hierarchical regression model: After a Bonferroni correction, better inhibition was a positive predictor of immediate LF- (B=.18, p=.040; covariates: sex, education, and perceived threat and control) and HF-HRV (B= .21, p=.020; covariates: education and perceived threat) recovery, and delayed HF-HRV recovery (B=.21, p=.020; covariates: education and perceived threat)

Table 2 (continued).

Study	Sample	Executive Functioning Facets and Tasks	Acute Stressor	Stress Phases and Outcomes	Findings
Morrison (2014)	*N*=105; M_{age}=18.04 (0.20); 62.90% female	Attention: Orienting threat bias on Modified Probe Detection Task; Threat disengagement bias on Posner Spatial Cueing Task; Response latencies on Attention Network Test Inhibition: Antisaccade Task RT and accuracy	Laboratory: TSST	Reactivity: • Salivary cortisol: peak cortisol; residualized change score (peak cortisol after covarying baseline cortisol)	Bivariate correlations: no significant associations between EF and peak cortisol Hierarchical multiple regression model: Interaction between Antisaccade RT and threat disengagement was positive predictor of cortisol reactivity (β=.90, t=3.43, p=.001); covariate: sex (not age as it did not correlate with cortisol)
Otto et al., (2013)*	*N*=56 in original study, *N*=20 for results for meta-analysis; M_{age}= 25.65 (7.33); 55% female	Working memory: Automated Operation Span score	Laboratory: CPT (*N*=20) vs. control room-water group (*N*=36)	*Obtained by email*: Reactivity: • Salivary cortisol: POST-CPT – PRE-CPT	Pearson product-moment correlations: no significant associations for individuals who underwent the stressor
Panganiban, (2013)	*N*=92; M_{age} not reported; 61.96% female	Inhibition: Proportion of stop responses on the Stop-Signal Task; RT difference between Stroop Task congruent and incongruent trials Cognitive Flexibility: Shift cost on Number-Letter and Local-Global Tasks Updating: Proportion of correctly recalled letters or words on the Letter Memory and Keep-Track Tasks	Field stressor: negative feedback messages during unmanned aerial vehicle simulation vs. no feedback control group	Reactivity: • Retrospective (post-stressor) self-reported distress while performing the task, using the Dundee Stress State Questionnaire	Correlations: in low task load, better updating associated with less distress (r(92)= -0.06, p<.05) Hierarchical multiple regression model: Controlling for stress group, better inhibition (β = -.18, p <.05) and worse updating (β =.26, p <.01) predicted less distress, threat appraisal, and situational uncontrollability over the stressor

Table 2 (continued).

Study	Sample	Executive Functioning Facets and Tasks	Acute Stressor	Stress Phases and Outcomes	Findings
Pilgrim et al., (2010)	N=25; M_{age}= 23.00 (4.00); 56.00% female	Attention: Attentional engagement and disengagement scores on Posner Spatial Orienting Paradigm for stress- neutral and positive-neutral material	Laboratory: modified TSST	Reactivity: • Salivary cortisol: AUC_i; percentage increase: [(PEAK – PRE-TSST)/PRE-TSST] • DBP, SBP & HR: did not report the outcome	Pearson product-moment correlations: significant correlation between stress-neutral engagement scores and AUC_i (r(25)= -.44, p=.03, r^2= .19); covariates: sex and past income Multivariate analyses: significant difference between slow- and fast-engagers. 81% of the latter showed cortisol increase against -3% decrease in slow engagers (t(23)=2.64, p=.02, d= 1.07)
Quaedflieg et al., (2019)*	N=112 in original article, 52 for meta-analysis; M_{age}= 22.32 (2.81); 49.09% female	Working Memory Total score on Forward and Backward Digit Span Task	Laboratory: MAST (N=56) vs. control (N=56)	*Obtained by email:* Reactivity: • Salivary cortisol: PEAK – PRE-MAST Recovery: • Salivary cortisol: LAST – PEAK	Pearson product-moment correlations: no significant associations for individuals who underwent the stressor
Quinn et al., 2019	N=39; M_{age}= 18.58 (0.60); 69.20% female	Updating Number of errors on Affective 2-Back Task	Laboratory: TSST (N=23) vs. control task (N=16; discussion about movie, novel or trip and arithmetic task)	Reactivity: • Salivary interleukin-1b, interleuking-6, and tumor necrosis factor-α: POST-STRESS – BASELINE	Correlations: no significant association between baseline updating and change in physiological measures Multiple regression model: Baseline updating did not significantly predict reactivity; covariates: gender and family income
Roelofs et al., (2007)	N=20; M_{age}= 22.10 (4.20); 90.00% female	Attention Angry and happy Attentional Bias Scores on Emotional Stroop	Laboratory: TSST	Reactivity: • Salivary cortisol: [(PEAK – PRE-TSST LOWEST VALUE)/PRE-TSST LOWEST VALUE] • DBP, SBP and HR: Results not reported	Two-way repeated measures ANOVA: Compared to low responders, high responders to TSST showed negative (avoidant) attentional bias to threat at baseline (F(1,18)= 5.55, p<.005, n^2= 0.24); covariates: gender, menstrual cycle, and oral contraceptives

Table 2 (continued).

Study	Sample	Executive Functioning Facets and Tasks	Acute Stressor	Stress Phases and Outcomes	Findings
Roos et al., (2017)*	*N*=97, 51 with full results in stress group; M_{age} missing; 52.94% female	Inhibition: Stop-Signal RT on Stop-Signal Task	Laboratory: TSST (*N*=58) vs. quietly reading a magazine (*N*=39)	*Obtained by email*: Anticipation: • HR and HF-HRV: PREAPARATION – BASELINE Reactivity: • HR and HF-HRV : TSST – BASELINE	Pearson product-moment correlations: Significant positive correlation between inhibition and HF-HRV anticipation (*r*(51)=.44, *p*=.001) for individuals who underwent the stressor
Sanchez et al., (2017)	$N_{total=}$30 adults; 22 adults with minimal depressive symptoms; M_{age}= 23.45 (4.23); 86.36% female	Attention: Attentional engagement and disengagement scores on an Attentional Engagement-Disengagement Task	Laboratory: speech-giving on why one is a good friend	*Obtained by email:* Reactivity: • HRV (RMSSD) and tension VAS: STRESS – PRE-STRESS Recovery: • HRV (RMSSD) and tension VAS: POST-STRESS – STRESS	Pearson product-moment correlations: Time to disengage from happy faces (*r*(22)= -.50, *p*=.017) and to engage with both disgusting (*r*(22)= -.60, *p*=.003) and sad faces (*r*(22)= -.55, *p*=.008) was negatively associated with tension reactivity Engagement time with disgust stimuli was negatively associated with tension recovery (*r*(22)= -.49, *p*=.021)
Schwerdtfeger & Derakshan, (2010)*	*N*=70; M_{age}= 33.51 (10.60); 50% female	Attention: Engagement and disengagement scores for angry and happy faces on Spatial Cueing Task	Laboratory: speech task in front of camera and experimenter	*Obtained within article:* Recovery: • HF-HRV: difference from baseline *Obtained by email*: Anticipation: • HF-HRV and RMSSD: PREPARATION PERIOD – POST-EF Reactivity: • HF-HRV and RMSSD: TASK – POST-EF Recovery: • HF-HRV and RMSSD : RECOVERY – SPEECHTASK	*Obtained within article:* Correlations: no significant association between engagement or disengagement for angry faces and HF-HRV recovery Stepwise hierarchical regression model: Disengagement from angry faces negatively predicted HF-HRV reactivity (vagal withdrawal; β= -.27, r_p = -.27, *T* = -2.18, $p < .05$); covariates: age, sex, caffeine, and smoking *Obtained by email:* Pearson moment-product correlations: significant association between disengagement from angry and change in anticipatory HF-HRV (*r*(70)=-.26, *p*=.029) and RMSSD (*r*(70)=-.28, *p*=.021). Longer times to disengage associated with less HRV change during anticipation phase

Table 2 (continued).

Study	Sample	Executive Functioning Facets and Tasks	Acute Stressor	Stress Phases and Outcomes	Findings
Xin et al., (2019)*	N=54; M_{age}= 22.57 (1.67); 35.19% female	Inhibition: Proportion of error on no-go trials in the Go/No-Go Task	Laboratory: TSST	*Obtained within article:* Exposure: • Recent stressful life events Reactivity: • HR and HRV (RMSSD and HF-HRV): MEAN-TSST – BASELINE Salivary cortisol: PEAK – BASELINE *Obtained by email:* Reactivity: see above Recovery: • HRV: RECOVERY – TSST • Salivary cortisol: LAST – PEAK	Independent samples T-tests: Participants with high and low EF did not differ in recent life events Moderation analysis: For participants with low – not high – inhibition, inhibition moderated the relationship between recent life events and change in RMSSD (t=2.79, p=.008, 95% CI [0.75, 4.59]), and HF-HRV (t=2.74, p=.009, 95% CI [32.28, 210.28]); covariates: sex and neuroticism Pearson moment-product correlations (obtained by email): significant associations between inhibition and cortisol reactivity (r(54)=.42, p=.001), and recovery (r(54)= -.39, p=.003)

Notes: * indicates study included in the meta-analysis; AA = Alpha-amylase; $AUC_{g/i}$ = Area under the Curve from the ground/increase; BMI = Body Mass Index; CPT = Cold Pressure Test; DBP = Diastolic Blood Pressure; HF = High Frequency; LF = Low Frequency; HR = Heart rate; HRV = Heart Rate Variability; *M* = Mean*; MAST*= Maastricht Acute Stress Test; *N* = Number of participants; *RT* = Reaction Time; PASAT = Paced Auditory Serial Addition Test; RMSSD = Root Mean Square of Successive Differences; SECPT = Socially-evaluated Cold Pressure Test; SBP = Systolic Blood Pressure; SCL = Skin Conductance Level; TSST = Trier Social Stress Test; VAS = Visual Analog Scale; WCST = Wisconsin Card Sorting Task.

Table 3

Characteristics of Interventional Studies included in the Systematic Literature Review

Study	Sample	Intervention	Acute Stressor	Stress Phases and Outcomes	Findings
Attention					
Baert et al., (2012)	*N*=28; M_{age}= 26.70 (6.60); 59.38% female; Training: *N*=14 Active CTRL: *N*=14	Training: six-day at-home Computerized Dot-Probe Training to disengage from negative stimuli and simultaneously engage with positive stimuli (dot replaces the happy faces on 90% of trials) Active CTRL: same task, cues, and number of trials, *without* modification of the contingency	Laboratory: mock job interview ahead of a real interview	Subjective stress: • Retrospective Tense VAS during stressor Reactivity: • HRV (RMSSD, LF, HF, LF/HF Ratio): Comparing baseline to measures from preparation to speech completion Recovery: • HRV (RMSSD, LF, HF, LF/HF Ratio): Comparing measures during baseline and follow-up post-stressor	ANOVA: Time*Group not significant for physiological or subjective reactivity. Stress increased regardless of group Paired samples t-tests: significant increase of RMSSD in training (t(13)=2.46, p=.03, d=30); significant increase in LF/HF ratio in CTRL (t(12)= 2.54, p=.03, d= 0.26) compared to training (t(13)=1.59, p=.14); further increase in LF units and decrease of HF units during recovery in CTRL, compared to no change in training group
Higgins & Hughes (2012)	*N*=64; M_{age}= 20.34 (3.39); 100% female; Training: *N*=34 Active CTRL: *N*=30	Training: 19-minute lab-based Computerized Anti-Negative Dot-Probe Task Training, inducing bias *away* from negative stimuli Active CTRL: same task, inducing bias *towards* negative stimuli	Laboratory: six-minute speech task in front of microphone	Reactivity: • DBP, SBP, and HR: Mean physiological levels during stressor Recovery: • DBP, SBP, and HR: Mean physiological levels after stressor	Repeated measures ANOVA: no main effect of group on DBP, SBP or HR ANOVA: For SBP, group*time* neuroticism interaction. In training group, participants high on neuroticism showed normal SBP following intervention. Those low on neuroticism showed higher reactivity. In CTLR, participants with high neuroticism had more pronounced responding to stressor, while those low on neuroticism had normal response.

Table 3 (continued).

Study	Sample	Intervention	Acute Stressor	Stress Phases and Outcomes	Findings
Pilgrim et al., (2014)	*N*=56; M_{age} not reported; 53.57% female; Masked: *N*=18 Supraliminal: *N*=18 Active CTRL: *N*=20	Masked: three-day (30-45min) lab-based Computerized Spatial Cueing Paradigm Training, disengaging attention from threat stimuli while engaging with positive stimuli, with mask presented after 17ms of facial cue Supraliminal: same training without mask Active CTRL: same facial stimuli but no attentional shift required	Laboratory: TSST	Reactivity: • Salivary cortisol and AA: AUC_g and AUC_i	ANCOVA: No group differences in cortisol AUC_g ANCOVA: Higher cortisol AUC_i in masked (*p*=.015, CI [1.33, 11.42]) and supraliminal (*p*=.008, *CI* [2.07, 12.81]) groups relative to controls; Supraliminals showed overall higher AA AUC_i (*p*<.001, CI [4974, 11.25] and AUC_g than CTRL (*p<.001*, CI [5516, 17.68)], and higher AUCi (*p*=.002) and AUC_g relative to masked (*p*=.013) Hierarchical multiple regression model: Training group (β = 7.44, *t*=3.45, *p*=.01) and baseline attention*group interaction (β = -.13, *t*=-2.24, *p*=.03) significantly predicted cortisol AUC_i (but not sAA); covariate: BDI-II Simple slope analyses: Training increased reactivity in those with high – not low – attentional control
Pilgrim et al., (2017)	*N*=69; M_{age} not reported; 60.87% female; Spatial cueing: *N*=16 Dot-probe: *N*=15 Active CTRL: *N*=19 Passive CTRL: *N*=19	Training 1: five-day (30-45min) at-home Computerized Spatial Cueing ABM Training 2: Dot-probe ABM Active CTRL: Gender Identification Task with no attentional shift required Passive CTRL: daily routine as usual	Laboratory: two TSSTs, two months apart	Reactivity: • Salivary cortisol: AUC_i Habituation: • Salivary cortisol: change in cortisol AUC_i between TSST 1 and 2	ANOVA: Compared to P-CTRL, spatial cueing (*F*(1, 65) = 5.74, *p* = .02, CI [0.53, 5.84]) and A-CTRL (*F*(1, 65) = 4.03, *p* = .05, CI [0.01, 5.09]) showed elevated AUC_i to first TSST; covariate: sex ANOVA: Group*phase interaction. Cortisol reactivity lower in follow-up TSST 2 (compared to TSST 1) in Dot-Probe (*F*(1,42) = 4.72, *p* = .035, CI [-5.198, -0.19]) and Spatial Cueing (*F*(1,42) = 4.71, *p* =.036, CI (-5.19, -0.19)) compared to P-CTRLs; covariate: sex Hierarchical multiple regression model: statistical trend towards baseline attention*group interaction (β = -.06, *t*(46)=-1.91, *p*=.06) predicting TSST cortisol reactivity Simple slope analyses: participants with low – but not high – baseline attention presented less cortisol reactivity in both training groups compared to CTRLs (*b* = -3.48, t(46) = -2.54, p = .01)

Table 3 (continued).

Study	Sample	Intervention	Acute Stressor	Stress Phases and Outcomes	Findings
Working Memory					
Quinn et al., (2014)	*N*=59; M_{age}= not reported; 44.07% female; Affective Training: *N*=23 Neutral Training: *N*=23 Affective CTRL: *N*=23	Affective training: One-session (35min) lab-based Adaptive N-Back Task (1-, 2-, 3-, or 4-back) with affective words (456 trials) Neutral training: same task with neutral words Affective CTRL: N-Back with simple target recognition	TSST	Reactivity: • Salivary cortisol: POST-TSST – BASELINE	ANOVA: No significant group*time interaction for cortisol reactivity Hierarchical linear regression model: Rumination did not significantly predict cortisol reactivity in the combined training group (*p*=.70) but did in CTLR (β=.78, $t(62)=4.32$, $p<.001$). At one SD above the RRS mean, participants in the training groups had *lower* cortisol relative to those in the control group ($\beta = -.53$, $t(62) = -3.77$, $p< .001$); covariates: BDI-II and RRS

Notes. AA = Alpha-amylase; ABM=Attentional Bias Modification; $AUC_{g/i}$ = Area under the Curve from the ground/increase; BDI-II = Beck Depression Inventory-II; CORT = Cortisol; CTRL = Control group, A=Active, P=Passive; DBP = Diastolic Blood Pressure; HF = High Frequency; LF = Low Frequency; HR = Heart rate; HRV = Heart Rate Variability; RMSSD = Root Mean Square of Successive Differences; RRS= Rumination Responses Scale; SBP = Systolic Blood Pressure; TSST = Trier Social Stress Test; VAS = Visual Analogue Scale