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Cognitive-motor interactions in dual-task paradigms in healthy and chronic stroke participants

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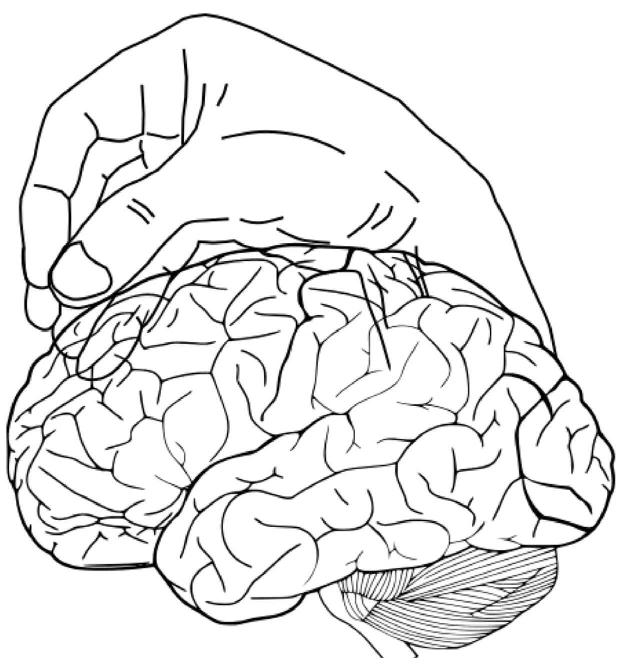

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Tempus fugit

The scariest moment is just before you start.
(S. King)

To you who are holding this work between your hands right now.

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List of Abbreviations

Aff	Affected hand of chronic stroke participants
CF	Coefficient of Friction
CMi	Cognitive-Motor interference
CNS	Central Nervous System
fMRI	functional Magnetic Resonance Imaging
GF	Grip force
GFmax	Maximal Grip Force apply on the object
GFhold	Average of Grip Force apply on the object while the object is held in the air
ICF	International Classification of Functioning, Disability and Health
Less	Less affected hand of chronic stroke participants
LF	Load Force
M	Motor task only (the precision grip-lift-hold task)
M + L	Motor and Low load Cognitive dual-task (semantic memory)
M + H	Motor and High load Cognitive dual-task (working memory)
MMSE	Mini–Mental State Examination
WK	Working Memory

CHAPTER I. INTRODUCTION

“We have a brain for one reason and one reason only - that’s to produce adaptable and complex movements. Movement is the only way we have affecting the world around us… I believe that to understand movement is to understand the whole brain. And therefore it’s important to remember when you are studying memory, cognition, sensory processing, they’re there for a reason, and that reason is action.” (Wolpert, n.d.)

DEFINITIONS AND OVERVIEW

We live in a busy and complex world. To interact with such a world we usually perform several tasks almost always at the same time. As hominids, object manipulation is our main way to interact with our environment. On a regular day, given all the things we have to do and given all the torrent of information coming at us at each instant, it is challenging to remember one moment when we are focusing on one and only one task. Indeed, in our daily life, object manipulation is most often performed concomitantly to other tasks involving higher-order cognitive functions such as taking notes while attending a lecture, keeping a number in memory while typing on a cell phone, or manipulating a filled glass while having a conversation.

As a student in physiotherapy, I have been taught many rehabilitation techniques to facilitate patient recovery after a disease, an accident or a surgery leading to functional deficits and activity limitations. What struck me the most was the analytical approach used to treat our patients, by focusing our cares on one limb or joint at one time. Almost all of these cares focused strictly and only on a body structure or a body function at one time. Patients allocate their entire attention on the gesture they had to perform and only on it. This could be sought and requested at first on purpose to enhance the quality of the gesture recovery. However, this kind of behaviour is more similar to what is observed in harsh and repetitive tasks like industrial production chain work, than what we do in our everyday life. Previous classic rehabilitation programs focus either on motor rehabilitation in physiotherapy or on cognitive rehabilitation in neuropsychology.

Very few rehabilitation protocols, reported in the scientific literature, tackle the dual-tasking activity of everyday life (Fritz et al., 2015), i.e. performing a motor task and a cognitive task at the same time like an usual activity.

According to the International Classification of Functioning, Disability and Health (ICF), (Figure 1.0. & Box 1.1.), the majority of upper limb evaluation and rehabilitation techniques focus on body structures and body functions of the model (Santisteban *et al.*, 2016). With respect to this model, the evaluation of a dual-task provides us with information on the dual-task activity of the participants.

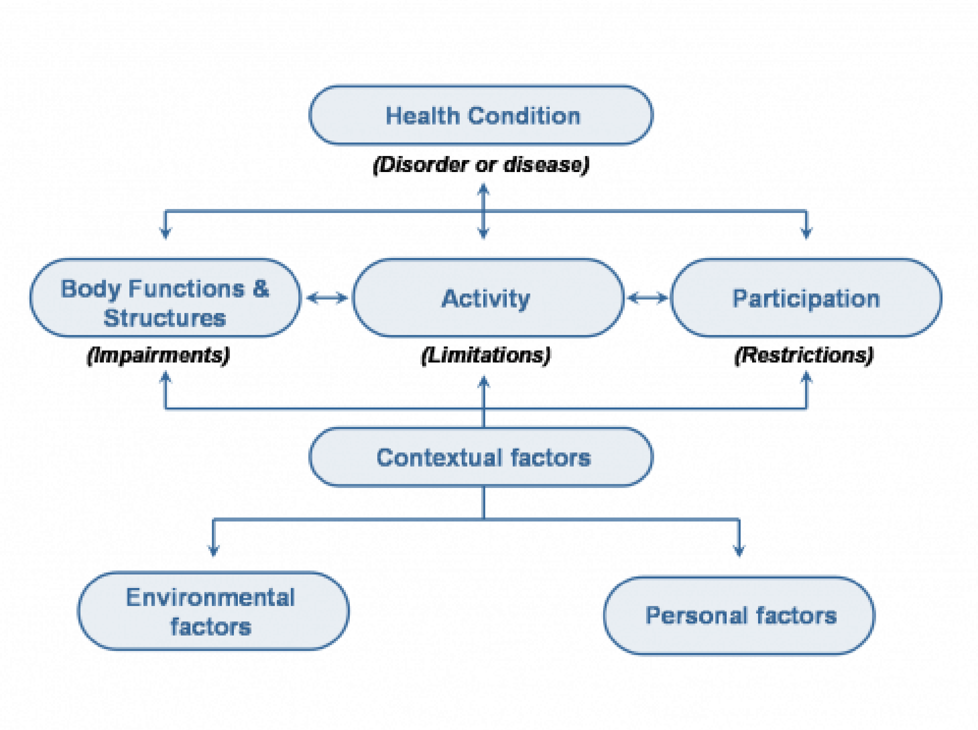

Figure 1.0. International Classification of Functioning, Disability and Health model diagram (ICF) (http://www.rehab-scales.org/images/blocks/1176903286/image-1.png?1176975371)

The ICF model describes functioning from three perspectives: body, person and societal. A first part of the model deals with Functioning and Disability, a second part with contextual factors.

The **Functioning and Disability** part of the model is divided into:
1. a **Body** component, including the structural or anatomical parts of the body (such as organs, limbs, and their components) and the physiological functions of body systems (its refers to the human organism as a whole and this includes the brain). A problem in this component is called **impairment**;
2. an **Activity** component, defined as the execution of a task or action by an individual, at personal level. A difficulty in this component is noted as an activity **limitation**; and
3. a **Participation** component, defined by involvement in real life situations, at the societal level. A trouble in this component is called a participation **restriction**.

Contextual factors are an independent and an integral component of the classification which is divided into:
1. **environmental** factors, factors that are not within the person's control, such as family, work, government agencies, laws, and cultural beliefs; and
2. **personal** factors, include race, gender, age, educational level, coping styles, etc.
Thus the conceptualisation provided in the ICF makes it impossible to understand disability without consideration and description of the environmental factors.

Box 1.1. International Classification of Functioning, Disability and Health model description
(http://www.who.int/classifications/icf/en/)

How do we manage to perform several tasks at the same time, despite our limited cognitive resources? Is there an evolution with ageing? Can chronic stroke participants perform dual-task despite critical brain damages and functional brain reorganization? In this thesis, we used cognitive-motor paradigms to examine whether dexterous manipulation, a highly habitual and seemingly automatic behaviour, involves high order cognitive functions in healthy and chronic stroke participants.

While both the clinical and neuroscience communities agree on the relevance of assessing and quantifying upper limb function and its coordination, rehabilitation engineers struggle to translate the knowledge and needs of clinicians and neuroscientists into technological devices for the patients (Shirota *et al.*, 2016). Given the many professionals with different areas of expertise and the broad range of research fields who get involved in dual-tasks behaviour, the main notions mentioned in this thesis are defined in the following paragraphs of this chapter, including dexterous, manipulation, working memory, and the dual-task paradigm. The choices of our motor and cognitive experimental tasks and target populations, the young and older healthy participants and chronic stroke participants, will be explained at the same time.

I.1. Dexterous manipulation

Despite its apparent easiness dexterous manipulation is a complex behaviour. Actually, the skill of grasping an object requires the integration of sensory (Gordon et al. 1991; Johansson et al. 2010), motor (Johansson & Westling 1984) and cognitive information (Olivier et al. 2007; Grafton 2010). Importantly, to narrow the field of research, we will focus on the grasping subtask of dexterous manipulation. It also brings insightful quantitative data about motor control.

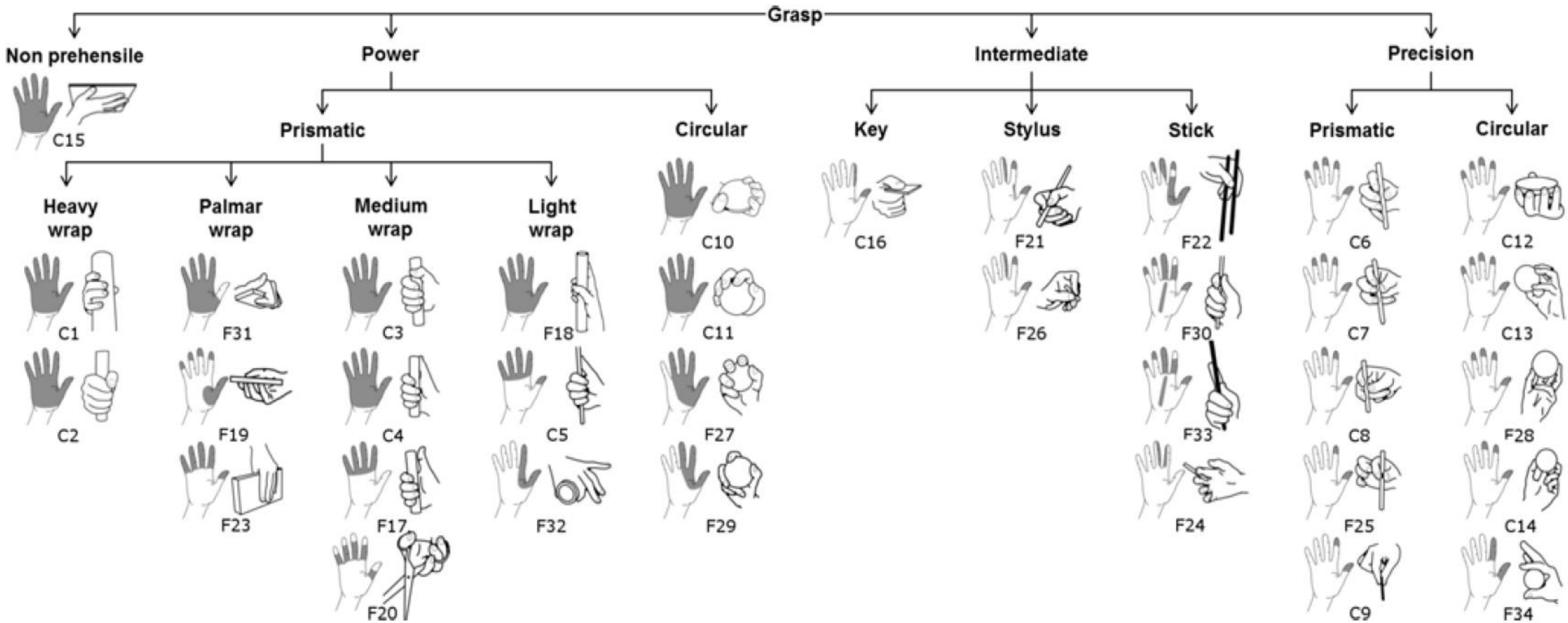

Figure 1.1.1. A comprehensive grasp taxonomy From (Gonzalez, Gosselin and Bachta, 2014). Illustration of the complexity of human grasp taxonomy. Classification according to merged taxonomy of Cutkosky, based on reduced number of potential contact areas between the hand and a haptic interface, with the taxonomy of Feix, based on grasp types (Cutkosky, 1989; Feix *et al.*, 2009).

I.1.1. Grasping taxonomy

Among the rich and elegant manner our hands interact with objects in our environment, we can describe probably as many grasping behaviours as existing objects in the world and their contexts of use. Several studies have suggested their own classification and taxonomy of grasping, leading to excessively elaborate and documented behaviour repertoire. Figure 1.1.1. illustrates the many ways we can grasp objects according to the hand contact area and grasp types (Gonzalez, Gosselin and Bachta, 2014).

The following types of hand grasping behaviour are probably the most usual, and functional (Feix et al., 2016; Napier, 1956). The *Power Grasp*, the opposition of fingers and palm, with the thumb in abduction as for a power task; the *Pinch Grip*, the opposition between the pad of the thumb and the ventral face of the other fingers; and the *Precision Grip* as the opposition between the pads of the thumb and the index.

I.1.2 Precision grip as a model of dexterous manipulation upper limb movement

The precision grip-lift task has been extensively studied in the literature and was historically described by Johansson and Westling in 1984, (Johansson and Westling, 1984; Westling and Johansson, 1984). A review of their initial work with dynamic and neurophysiological data is published in 2009 (Johansson and Flanagan, 2009a). Precision grip is a learned skill that reaches its mature control at the age of 6 or 8 years old (Forssberg *et al.*, 1991). Since then, the precision grip-lift task is a fast adapted behaviour and remains stable across repetitive trials in a healthy population (Johansson and Westling, 1984; Westling and Johansson, 1984). It consists in subtle coordination of the Grip Force (GF), normal forces applied on the object to prevent its slip, and the Load Force(LF), tangential forces that fight against gravity and inertia to load and lift the object (Johansson and Westling, 1984; Westling and Johansson, 1984).

We use the precision grip-lift task as our main motor task and as a model of fine dexterous manipulation of the upper limb. To our knowledge, it is the most precise and accurate evaluation of precision grip and dexterous behaviour. This evaluation brought insightful quantitative data, allowing us to make a precise description of the function of grasping and lifting an object. Figure 1.1.2. illustrates a typical precision grip movement linked with the major sensorimotor events guiding the behaviour.

Sensorimotor processing is associated with inherent time delays and noise. The conduction of afferent and efferent neural signals, and the processing of signals are limited in time by the constraints of their neurophysiological substrates. Synaptic transmission delay is about 10ms in chemical synapses (Purves *et al.*, 2018), and from 0.5 to 4ms in the neuromuscular junction (Katz and Miledi, 1965). Slowest propagation of electrical signals along the membrane of nerve fibres has a transmission speed of at least $0.5 m.s^{-1}$.(Purves *et al.*, 2018). For example, the fastest muscle respond to a stimulation, called the spinal monosynaptic reflex, takes about 18ms (biceps brachii) (Hammond, 1955), while the reactive correction to a sudden change in load force of a manipulated object takes 70 to 150ms (Johansson and Westling, 1988b; Wing *et al.*, 1999; White *et al.*, 2008). In the context of motor control, noise means an alteration of sensory signals by irregular fluctuations at the level of the peripheral sensory receptors as well as the peripheral and central neurons (Faisal, Selen and Wolpert, 2008). To face inherent delays and noise of sensorimotor processing, both grip and lift forces must be programmed in anticipation of the expected sensory events arising from the manipulation (Wolpert and Flanagan, 2001; Flanagan, Bowman and Johansson, 2006).

To perform such skilled hand movements, two type of process have been distinguished (Woodworth, 1899; Elliott, Chua and Helsen, 2001), a planning phase, in which the movement is prepared and initiated without sensory feedback, and an online control phase, in which the movement execution is monitored with afferent feedbacks (Wolpert and Ghahramani, 2000; Glover, Wall and Smith, 2012). This leads to the notion of internal models, i.e. how our central nervous system (CNS) represents the physical world (Wolpert, Ghahramani and Jordan, 1995), or even how we can predict the future (Bubic, 2010).

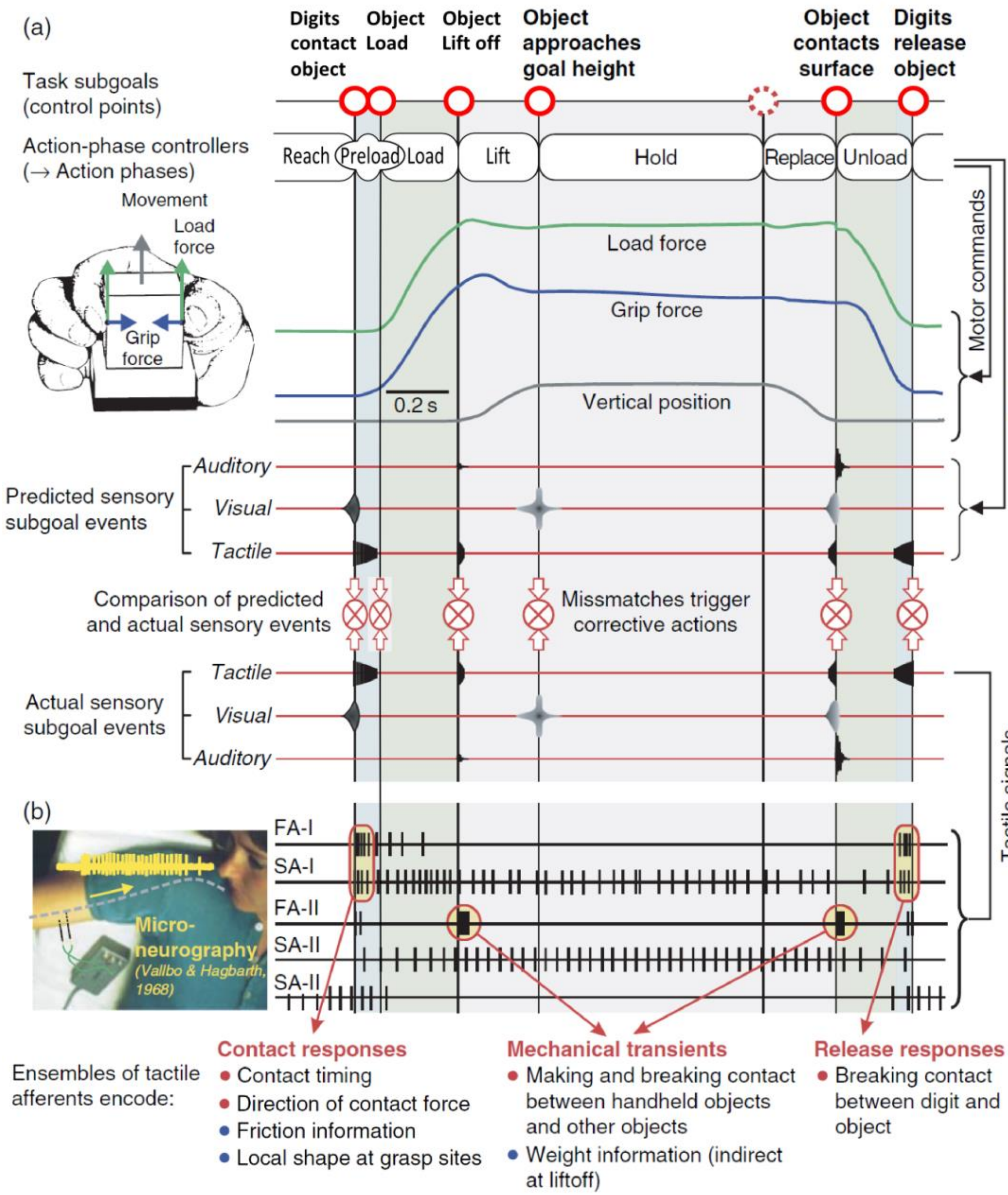
(a)
Task subgoals (control points)
Action-phase controllers (→ Action phases)
Digits contact object
Object Load
Object Lift off
Object approaches goal height
Object contacts surface
Digits release object
Reach
Preload
Load
Lift
Hold
Replace
Unload
Movement
Load force
Grip force
Load force
Grip force
Vertical position
0.2 s
Motor commands
Sensory predictions
Predicted sensory subgoal events
Auditory
Visual
Tactile
Comparison of predicted and actual sensory events
Missmatches trigger corrective actions
Actual sensory subgoal events
Tactile
Visual
Auditory
Tactile signals
(b)
FA-I
SA-I
FA-II
SA-II
SA-II
Micro-neurography
(Vallbo & Hagbarth, 1968)
Ensembles of tactile afferents encode:
Contact responses
• Contact timing
• Direction of contact force
• Friction information
• Local shape at grasp sites
Mechanical transients
• Making and breaking contact between handheld objects and other objects
• Weight information (indirect at liftoff)
Release responses
• Breaking contact between digit and object

Figure 1.1.2. Tactile Sensory Control of Object Manipulation

Adapted from (Johansson & Flanagan, 2009)

(a) Precision grip is characterized by a sequence of action phases separated by contact events that define subgoals: the Preload, Load, Lift, Hold, Replace and Unload phases. After digits contact the object, the GF increases in parallel with the tangential LF applied during isometric conditions to the object to overcome gravity. When the finger stop to slip on the object, the LF starts to increase in parallel with the GF. When the LF overcomes the force of gravity, the object lifts off. After the object is replaced, it contacts the support surface and the load and grip forces decline in parallel until the object is released. In conjunction with generating motor command, the action-phase controllers predict internally the sensory consequences of these commands in one or more modalities (predicted sensory subgoal events), whereas the actual sensory consequences are signalled in one or more modalities (actual sensory subgoal events).

Compiled from data presented in (Westling and Johansson, 1987).

(b) Schematic illustration of signals in four types of tactile afferents innervating the human fingertips as recorded from the median nerve at the level of the upper arm using the technique of microneurography. FA-I afferents (fast-adapting type I) are firing when the object is contacted and released. FA-II afferents (fast-adapting type II) are relate to the transient mechanical events that accompany the object lifting off and being replaced on the support surface. SA-I afferents (slow-adapting type I) and SA-II afferents (slow-adapting type II) discharge when static forces are applied to the object.

From (Vallbo and Hagbarth, 1968).

I.1.3. Internal Models

Internal Models can be defined as the representation of the dynamical properties of both the body and the physical environmental world, based on the sum of our previous experiences (Wolpert, Ghahramani and Jordan, 1995). To explore and control our world, we have to make assumptions about what would be the consequences of our acts. Theoretical and computational studies suggested that the CNS internally simulates the behaviour of the motor system in planning, control and learning movements (Miall and Wolpert, 1996). Several types of internal models have been proposed (Wolpert and Flanagan, 2001). Using an efference copy of the motor command, forward dynamic models predict the future state of the body (e.g. its position), while forward sensory models predict the associated sensory consequences (Wolpert and Ghahramani, 2000). Inverse internal models implement the inverse transformation by generating motor commands based on the desired consequences of motor action (Kawato, 1999). These predictions facilitate the effective anticipatory control of action without depending on the delayed and noisy actual sensory feedback (Flanagan et al. 2006; Wolpert & Flanagan 2001). A mismatch between the predicted and the actual sensory input triggers corrections and updates the relevant forward models of both body and object.

To sum up, a feedforward process produces anticipatory behaviour on the base of the internal model to predict what is the best action to perform on a given time, in a given context. Feedbacks allow us to monitor our ongoing body state and our current movement progresses, and to update the current internal model.

How the CNS deals with the subtle coordination of the force applied to a manipulated object is a vivid application of internal models theory. In our experiments, feedforward anticipatory command based on an internal model is used to control the precision grip-lift task. It takes into account all learned sensorimotor information from the dynamic characteristics of the body and the upper limb and the predicted dynamic characteristics of the object (Gordon *et al.*, 1991). Thus, if the information given by the feedbacks mismatches the predictions of the internal model, a new feedforward input will be sent to correct the ongoing movement. This feedback information will update the current internal model (Shadmehr, Smith and Krakauer, 2010; Wolpert, Diedrichsen and Flanagan, 2011).

Basically, it is proposed that our CNS builds models of the physical world through learning by catch and retry.

In this thesis, we used cognitive-motor paradigms to examine whether dexterous manipulation involves high order cognitive functions. Importantly, in these experiments, we didn't aim to induce a learning effect in the motor or the cognitive tasks. On the contrary, we wanted to test two controlled and stable tasks with well-known processes. Otherwise, it could have led to uncontrolled interaction effects and difficult interpretations.

I.2. High-level cognition

In his book "*Attention and Effort*", published in 1973, Daniel Kahneman reviewed the basis of interference between concurrent tasks. In a dual-task paradigm, the interference effect is described in terms of a competition for a generally limited attention capacity (Kahneman, 1973). An outline of attentional capacity according to Daniel Kahneman is demonstrated in Box 1.2. Attention is commonly defined as a mental spotlight, allowing the selection of information and behaviours in a given context. A more scientific definition of attention is given by E. Bruce Goldstein in his book "*Sensation and Perception*" (Chapter 6) (Goldstein, 2009): "*Attention means devoting cognitive resources to specific features of the environment in such a way that causes those features to become more deeply processed*".

Attention is **limited**. Our attention capacity can be overloaded. When a task is made more complex, performance slows down and errors increase in spite of augmented attention engaged in the task.

Its limit is **variable** from moment to another, depending on many factors like context, awakening and primarily on the demands of current activities.

Attention is **divisible**. The allocation of attention is a matter of load. We can spread our attention between several tasks of low load. However at high-level of load it is not yet possible, we focus on only the demanding task

Attention is **selective**. We can allocate it to facilitate the processing of one selected perceptual task or the execution of one selected motor performance. In other words we can focus on one task to the detriment of others.

Box 1.2. Attention capacity according to Kahneman

The consequence of limited cognitive capacity is a slowing down or increasing error rate in activity performances. Especially when an activity relies itself on several tasks performed at the same time. These tasks could rely on share processes. The interferences between concurrent processes will depend in part on the load that each of the activities imposes, i.e. on the demands of each of the competing activities for cognitive resources. Thus performing two or more tasks concomitantly may have a cost. For example, we all face the situation while driving and conversing, when the demands of driving activity become critical we interrupt our conversation. When the demands of the two tasks cannot be adequately satisfied, one is typically selected and the other is delayed or abandoned. Sometimes, two tasks are performed accurately and correctly simultaneously, e.g. when walking and talking. The two tasks rely on different processes or at least one of the two tasks, walking in this example, is almost automatized, in other words, it required no or very little attention or higher cognitive process. Some other times, we find excessively difficult to execute two activities together although each one is easy to perform alone. For example, we can easily rehearse a phone number before making a call. Now if we try to remember the same number while a friend distracting us with a question, it is very likely that we forget the phone number after giving his answer. Indeed, the interference can arise even when the two activities do not share obvious mechanisms in either perception, processing or response.

The concept of attention was constructed colloquially to describe introspectively accessible human experiences since millennia, nevertheless, it is still debated in the literature (Anderson, 2011). Its concept is difficult to disentangle from the concept of consciousness or executive control. At a neurophysiological stage, attention is no more assumed as a unitary process. These different attentional processes are mediated by different neural networks. Although the exact nature of these networks and the degree to which they are independent is still not clear (Raz & Buhle, 2006). Nowadays, the more consensual notion in the literature about control and regulation of attention and cognitive resources is the working memory process.

I.2.1. Working memory as a model of high-level cognitive process

There is a growing body of evidence to suggest attention control and working memory (WM) are closely intertwined (Torta *et al.*, 2017). Actually, Kiyonaga proposes that working memory and attention should no longer be considered as separate systems or concepts, but as competing and influencing one another, because they rely on the same limited resource (Kiyonaga and Egner, 2013). The nature of these interactions depends upon the specific variety of attention, or WM, that is considered (Awh, Vogel and Oh, 2006; Chen *et al.*, 2017). Since WM operates over the same representations as attention, it has been proposed that WM is internally directing attention (Benedek *et al.*, 2016; Chen *et al.*, 2017). This is consistent with the concept of mental spotlight described in early neuropsychological studies.

Besides its role in short-term storage of sensory inputs (Aubin *et al.*, 2007), working memory is also regarded as an executive function involved in monitoring control over information processing (Hegarty, Shah and Miyake, 2000) such as prioritizing the processing of relevant target stimuli from interfering distracters (Lavie and De Fockert, 2005). For instance, in a dual-task combining an attentional task with a working memory task, De Fockert et al. (de Fockert *et al.*, 2001) showed that the performance of the attentional task was decreased when working memory abilities were captured by a second unrelated task. Conversely, the ability to control distraction to irrelevant sounds (SanMiguel et al. 2008) and nociceptive stimuli (Legrain *et al.*, 2011, 2013; Legrain, Crombez and Mouraux, 2011), is increased when the participants are encouraged to use working memory abilities to perform the attentional task. The difference in interaction effects may rely on the different neural pathways of the different processes involved in the different experiments. In regard to these results, a working memory task (a task that specifically recruits working memory process) can be assumed to modulate attentional executive functions.

I.2.2 Perceptual load theories

Perceptual load theories (Lavie and De Fockert, 2005) propose that attentional effects on any sensory processing depend on the interaction between task difficulty and stimuli features. Perception has limited capacity but processes all stimuli in an automatic mandatory fashion until it runs out of capacity. Thus, high perceptual load that engages full capacity in relevant processing would leave no spare processing capacity for perception of task-irrelevant stimuli. However, in situations of low perceptual load, any remaining processing capacity not taken up in the perception of task-relevant stimuli would involuntarily spread to the perception of task-irrelevant distractors.

In our experiments, we use this concept of load on cognitive functions to assess the needs of high-level cognitive processes on dexterous manipulation. By manipulating working memory we want to modulate the needs in executive functions in a cognitive task. This cognitive task is designed to recruit as much as possible cognitive resources. In dual-task condition, if high-level cognitive processes are involved in the motor task, there will be a competition with those already involved in the concurrent cognitive task, resulting on errors in one or two of the motor or cognitive tasks. Importantly, we designed our cognitive task to minimize the involvement of motor control and motor imagery. Otherwise, it could have led to obvious competition with our concurrent motor tasks.

I.3. Dual-Tasks

Multitasking was examined by many different paradigms from divergent fields of research, from engineers, clinicians, teachers to performing artists; from movement and cognitive neuroscience to social science, and from the national department of Health to Department of Transport or even spatial agency (Mcisaac et al., 2015). Given the broad and several fields of research in the domain of dual-tasking and the absence of a frame of reference to study dual-tasks, the following paragraphs explain our chosen definition of dual-task and how interaction effects can be interpreted. The last paragraph is a short literature review of selected dual-tasks studies.

Actually, when facing two concurrent activities we eventually have two choices: dealing with them in parallel or sequentially. In the first case, the two tasks will be addressed at the same time, with increasing risk to get an interaction effect between the two tasks. In the other case, one of the tasks will be delayed in favour of the other, which can be called tasks-switching. Research on simultaneous dual-tasks and sequential tasks-switching has proceeded largely separately using different experimental paradigms and methodology (Koch *et al.*, 2018). Serial processing of tasks is predominantly adopted because its processing efficiency is reported higher than that of parallel processing (Han & Marois 2013), even when participants are rewarded to process both tasks in parallel (Ruthruff et al. 2009), however, it did not fit with the following definition of dual-task. This is why we did not choose task switching paradigms in our experiments.

There is still no official consensual recommendation about dual-task paradigm. In this thesis, we keep up to the definition of dual-tasking recommended by Tara McIsaac: "Dual-task is defined as the concurrent performance of two tasks that can be performed independently and have distinct and separate goals" (Mcisaac et al., 2015). This implies that each task performance has to be measured independently as a single task before performing them simultaneously. These tasks should be independent and unrelated in terms of behaviour. A priori no prioritisation instruction over a task or the other should be given.

The concurrent performance of a cognitive and a motor task can yield to nine different patterns of cognitive-motor interactions (Figure 1.3.). This includes four major isolated changes (motor task facilitation, motor task interference, cognitive task facilitation and cognitive task interference), or the possible combinations of these observations, as well as no changes at all (Plummer *et al.*, 2013).

		Cognitive performance		
		No change	**Improved**	**Worsened**
Motor performance	**No change**	No dual-task interference	Cognitive facilitation	Cognitive interference (motor-related)
	Improved	Motor facilitation	Mutual facilitation	Motor-priority trade-off
	Worsened	Motor interference (cognitive-related)	Cognitive-priority trade-off	Mutual interference

Figure 1.3. Pattern of cognitive-motor interference (CMi) in dual-task experiment. Adapted from (Plummer *et al.*, 2013)

Dual-tasking is more than the simple sum of two tasks execution (Szameitat, Schubert and Müller, 2011). The interactions between two presupposed distinct and incongruent tasks give us information about mental processes proper to one of the tasks or those that are common or shared between the tasks. For example, shared attention has direct implications for safety: we are all aware of the danger of using a phone while driving (Strayer, Watson and Drews, 2011), listening to music when walking beside a railway or while reading when walking down the street.

Since interference effects occur when the demands of the concurrent tasks exceed the available processing capacity of the performer, another application of dual-tasks is to evaluate the actual processing capacity of patients. Thus, monitoring normal ageing or deterioration processes in neurological patients. It could possibly quantify the limitations of a given treatment, develop and improve treatment goals.

The underlying mechanisms of the dual-task interaction are still debated in the literature. According to neuropsychologists, different theoretical models try to explain dual-task interaction including: capacity sharing (i.e., shared processing capacity or mental resources among tasks), bottlenecks (i.e., dual tasks need the same mechanism/resources at the same time), and cross-talk (i.e., interference in dual-tasking due to similarities in the content of information being processed) (Wickens, 1980; Abernethy, 1988; Pashler, 1994).

According to the limited-capacity bottleneck theory (Broadbent, 1958), we are unable to process all the available information simultaneously; therefore, a selection is required. This concept of bottleneck has been thoroughly studied, notably by the National Aeronautics and Space Administration in the United States of America, with complex and abstract reaction time tasks, associating visuo–manual and auditory-vocal tasks. It is revealing that with training, two tasks that initially interfere can then be simultaneously performed without interference anymore (Hazeltine, Teague and Ivry, 2002). This absence of dual-task interference does not necessarily indicate the absence of a processing bottleneck (Ruthruff *et al.*, 2003). Authors argue that with training, a perfect timing between the processing of the two tasks is achieved (Schumacher *et al.*, 2001, 2018)

According to the limited attentional resources model, when participants perform a highly demanding cognitive task, the attentional load will reduce the available resources needed to process task-irrelevant stimuli (Legrain et al., 2009). In our experiments, we use the concept of cognitive-motor interference to evaluate the involvement of high-level cognitive processes on dexterous manipulation by combining a motor grip-lift task to a working memory task.

According to McIsaac, in 2015 there were 944 studies about dual-tasks involving locomotion and posture, 143 about seated locomotion, but only 51 about upper limb behaviours (Table 1.3.1) (Mcisaac *et al.*, 2016). This imbalanced numbers could be explained by the relative differences in severity level brought by diseases in lower and upper limbs. Indeed, injury or disease affecting lower limb has more severe consequences on body functions, activities and participation, than those affecting the upper limb. These numbers may emphasize the need for further research involving upper limb behaviour.

Dual-Tasking Activities Studied	**Number of Publications by Activity**
Upright stance & locomotion	
Balancing / Postural control	375
Walking / Gait	569
Seated locomotion	
Driving	141
Bicycling	2
Manual tasks	
Reaching & Grasping	47
Dexterity	4

Table 1.3.1. Imbalanced number of publications about Dual-tasks according to different activities. Last update in 2015, adapted from (Mcisaac *et al.*, 2016)

Populations Performing Dual-Tasks Studied	Number of Publications by Population
Healthy young adults	241
Aging	429
Neurologic Involvement	
Parkinson Disease	146
Stroke	128
Traumatic Brain Injury	96
Multiple Sclerosis	40
Huntington's disease	10
Essential Tremor	4
Mild Cognitive Impairment	73
Dementia	173
Alzheimer's	127

Table 1.3.2. Number of publications about dual-task according to studied populations. Last update in 2015, adapted from (Mcisaac *et al.*, 2016)

Another striking number is the twice more dual-task studies involving ageing and a fortiori older adults than healthy young adults. (Table 1.3.2.) (Mcisaac *et al.*, 2016). However, the table does not give insight into the number of studies involving both types of population. The impacts of age and neurologic disease on motor, cognitive and dual-tasks are more detailed further paragraphs (I.4 & I.5).

In some dual-task studies, given the common nature of the concurrent processes involved in the concurrent tasks, the two tasks will obviously interact with each other. For instance, in motor-motor dual-tasks, such as in bimanual task, like bimanual liftings (Dimitriou and Buckingham, 2018) or in walking and upper limb gesture (Abbruzzese *et al.*, 2015), the two tasks are more likely to interact with each other since the coordination of different limbs relies on the same mental processes and the same neural pathways. Actually, the simultaneous performance of movements involving different effectors gives rise to neural (Carson, 2005) and biomechanical interactions between and within limbs (Li *et al.*, 2005). It is also the case in cognitive-cognitive dual-tasks, e.g. when two visual working memory tasks

(Cocchini *et al.*, 2002) or when verbal working memory and visuospatial memory are solicited (Fougnie and Marois, 2011), due to the overlapping nature of the processes involved in the two tasks.

One actual difficulty of designing a cognitive-motor dual-task paradigm is not to involve a motor process in the cognitive task or a non-motor cognitive process in the motor task. Then if it is meant on purpose, the interactions will be predictable. Every time a cognitive task will require a motor reaction as participant's responses, understandably, at time of the response of the cognitive task, the motor process will interact with those ongoing in the concurrent motor task.

Recent studies have shown that performing a higher-order cognitive task may interfere with the realization of upper limb movements. They used dual-task paradigms involving a motor task simultaneously performed with a cognitive task. Motor tasks range from a simple object manipulation like reaching and grasping task (Li et al., 2009; Spiegel et al., 2013, 2014; Gunduz Can et al., 2017), precision and power grip squeezing task (van Dijck et al., 2014); force tracking task (Voelcker-Rehage et al., 2007; Mehta and Agnew, 2011; Au and Keir, 2007; Temprado et al., 2015); reach and grasp familiar hand tools (Creem and Proffitt, 2001), tapping task (Serrien, 2009; Fraser et al., 2010; Korotkevich et al., 2015); to the complex cellists' bowing movements (Maes et al., 2015). In addition, several different cognitive processes were involved in their cognitive tasks: semantic memory: with action-related, or not, words (Creem and Proffitt, 2001; Glover and Dixon, 2002; Glover et al., 2004); associative memory (Li et al., 2009; Singhal et al., 2007); working memory : with Stroop task (Au and Keir, 2007; Mehta and Agnew, 2011), N-back tasks (Voelcker-Rehage et al., 2007; Gunduz Can et al., 2017), and counting task (Serrien, 2009; Fraser et al., 2010; Korotkevich et al., 2015) As a result, concurrent motor tasks interfere with WM and decrease memory performance. In these studies, the motor planning and the execution of the movement recruit the capacity-limited cognitive resources which are also required for performing the cognitive task (Spiegel et al. 2013). Motor tasks interfered with WM and the decrease was larger for the memory performances of the visuospatial task as compared to the verbal task (Weigelt et al. 2009). Electrophysiological data also reveal that in a dual-task condition involving visuospatial processes, ERPs changed only for the encoding process and not for the retrieval process of their custom motor task (Gunduz Can et al. 2017).

In this thesis, we used cognitive-motor paradigms to examine the interactions between a precision grip-lift task and concurrent cognitive tasks, thus, addressing the question of the involvement of high order cognitive functions in dexterous manipulation, in healthy and chronic stroke participants.

I.4. Healthy ageing

"*Surprisingly, provided the socioeconomic, medical, and public health advantages of Baby Boomers throughout their lives, they are not doing considerably better on all counts, when compared to the previous generation with less medical advantages.*" (Martin *et al.*, 2009).

The world's population is rapidly ageing, more quickly than the past. The number of people aged 60 years or older will rise from 900 million to 2 billion between 2015 and 2050 (moving from 12% to 22% of the total population) (World Health Organization, 2011b). With the ageing of the population, there is growing morbidity among ageing adults (Hoffman *et al.*, 2017).

"*Today we live longer, but this prolonged life expectancy has not necessarily gone parallel with sufficient maintenance of cognitive ability*" (Cahn-Weiner, Boyle and Malloy, 2002).

Healthy ageing is associated with alteration of the sensory and motor systems, processing capacity, sensitivity to distraction and cognition in general (de Dieuleveult *et al.*, 2017). Normal ageing typically reduces sensory sensitivity in multiple modalities including vision, (Wongrakpanich, Petchlorlian and Rosenzweig, 2016), hearing (Mormer *et al.*, 2017), olfaction and taste (Seiberling and Conley, 2004), somatosensory perception (Dunn *et al.*, 2015) and touch (Reuter *et al.*, 2012; Abdouni *et al.*, 2018; Skedung *et al.*, 2018). By comparison with young adults, older adults also exhibit a general slowing in both cognitive and motor processes (Serrien, Swinnen and Stelmach, 2000) leading to longer reaction and movement execution times. More time is needed to examine signals and discard neural noise, leading to increased processing demands and declines in coordinated activities. Effortful cognitive abilities, that consolidate relatively late in development, are the first to weaken with old age and information processing capacity regresses in later life (Hoffman *et al.*, 2017).

These behavioural observations are strongly supported by imagery data revealing several brain changes (Raz et al. 2005) and involvement of more widespread brain regions in motor control than young adults, particularly the prefrontal cortex, pre-supplementary motor area and basal ganglia networks (Seidler, 2010; Wolpe *et al.*, 2016).

The alteration of structures and functions of both sensory and motor systems must critically affect dual-tasking. In a dual-task situation involving the lower limb, older adults often show a higher cost of cognitive resources than younger adults (Li, Krampe and Bondar, 2005). Actually, the vast majority of dual-task experiments are related to risks of falling, falling-related injuries and falls prevention programs, as shown in Table 1.3.2. Regardless of the type of the affected population (e.g. normal ageing (Schrag *et al.*, 2015), with neurological diseases as Parkinson 's disease or Dementia (Kosse *et al.*, 2015)), fall-related injuries are a real threat in a clinical setting. In the USA, in 2008, the estimated medical expenditure of each injury due to a fall is ranging from 5,969 to 12,808 dollars and total medical insurance expenditures were 13 billion dollars (Hoffman *et al.*, 2017). Indeed, these injuries often result in loss of independence and increased health care utilization, associated with substantial and persistent medical insurance expenditures. For instance, two-thirds of seniors hospitalized for fall injury are later admitted to a long-term care facility (Owens, Russo and Mutter, 2009).

One of the principal causes of falls in older adults is the general impairment in both motor and cognitive functions. Since cognitive resources are reduced, dual-tasks in older adults become more and more challenging. Indeed a famous predictor of falls in older adults is the "Stops walking when talking" test (Hyndman and Ashburn, 2004). Someone in good health can speak and walk at the same time without concern. If a participant suffers from any alteration in motor function and/or cognitive function, a task involving this affected function will require an increasing need in cognitive resources to control, thus reducing the available cognitive resources for the concurrent task. In this example the increasing need for cognitive resources for speaking will deplete the available cognitive resources for controlling walking, eventually resulting in the fall of the patient. Hopefully, if a patient is aware of its own disease, he will adopt a safety strategy, by stopping the walk, to secure his posture and speak. Indeed, older adults tend to prioritize the motor task over the cognitive one, and it is even more pronounced when people are challenged a lot and when the motor task involves some threat to their balance (Verghese *et al.*, 2007; Yogev-Seligmann, Hausdorff and Giladi, 2012).

Less is known about dual-tasks involving the upper limbs. To our knowledge, there is no equivalent to evaluate the upper limb behaviour in dual-task context, and there is no study showing a priority of dexterous manipulation or cognitive tasks over the other.

I.5. Stroke resulting in motor impairment

The incidence of stroke ranged from 76 to 119 per 100000 population per year, with an increasing rate every year (Thrift *et al.*, 2017). It is one of the worldwide leading causes of long-term disability (Mensah, Norrving and Feigin, 2015). Motor dysfunction is the most prevalent impairment. Some studies are reporting over 90 per cent of stroke survivors suffering from upper limb motor disability (Parker, Wade and Hewer, 1986; Broeks *et al.*, 1999). Most of the improvement in motor and functional recovery of arm function occurred during the first 16 weeks after stroke (Broeks *et al.*, 1999; Kwakkel, Kollen and Twisk, 2006), but only approximately 12% of stroke survivors achieve complete motor recovery after 6 months (Kwakkel et al. 2003). Manual dexterity is frequently impaired in this population, resulting in long-term functional deficits (Bleyenheuft and Gordon, 2014).

In the grip-lift task, due to both sensory and motor deficits, post-stroke survivors typically exhibit excessive GF with the affected hand as compared to the less affected hand, (Hermsdörfer *et al.*, 2003; Nowak, Hermsdörfer and Topka, 2003; Wenzelburger *et al.*, 2005; Blennerhassett, Carey and Matyas, 2006; McDonnell *et al.*, 2006). They tend to often push down the object on the table before lifting it (McDonnell *et al.*, 2006). These alterations lead to a lengthening of the preload phase of the grip-lift behaviour (Hermsdörfer *et al.*, 2005; Blennerhassett, Carey and Matyas, 2006; McDonnell *et al.*, 2006). As compared to the less affected hand, the affected hand demonstrated irregular increases of grip and load forces with an alteration of the temporal coupling of the two forces. These alterations lead to a lengthening of the load phase (Hermsdörfer *et al.*, 2005; Blennerhassett, Carey and Matyas, 2006; McDonnell *et al.*, 2006). The increase of grip force already starts at the load force onset and this increase lasts even during the holding phase, i.e. when the apparatus is stabilized over the table. Accordingly, the difference between the actual grip force and the minimum force necessary to prevent object slipping, called the safety margin (SM) is also increased (Hermsdörfer *et al.*, 2003; Nowak, Hermsdörfer and Topka, 2003). These increased grip forces and deficits in temporal coupling of the grip and load forces are present in patients with cortical, subcortical and cerebellar stroke (Hermsdörfer *et al.*, 2003; Nowak, Hermsdörfer and Topka, 2003; Nowak and Hermsdörfer, 2006b; Anens, Kristensen and Häger-Ross, 2010), suggesting that the internal models responsible for precise regulation of forces are impaired. The predictive mechanism is present but altered in the paretic hand (Takahashi and Reinkensmeyer, 2003; Raghavan, Krakauer and Gordon, 2006). These alterations suggest an inability to anticipate the consequences of dynamic perturbations in the paretic hand (Dispa et al. 2014). The scaling and the coupling of grip and lift forces, were also significantly altered even in the presupposed unaffected hand, ipsilateral to the lesion, in patients with subcortical middle cerebral artery stroke (Quaney *et al.*, 2005; Nowak *et al.*, 2007).

To our knowledge, there are only a few studies evaluating dual-task paradigms with post-stroke survivors, and they all involved walking as the motor task (Pohl *et al.*, 2011; Plummer *et al.*, 2013; Wang *et al.*, 2015). In this thesis, a cognitive-motor paradigm was set up to assess chronic stroke participants in dual-task involving dexterous manipulation. It is an opportunity to examine the interactions between the precision grip-lift task and concurrent cognitive tasks in a population with persistent and a priori stable deficits in both predictive and reactive controls of movements. It also allows us to test if dual-task effects are present in both the affected and the less affected hand following stroke.

I.6. Thesis Overview

The aim of this thesis is to assess the involvement of high cognitive function in dexterous manipulation. We use a dual-task paradigm to evaluate the cognitive-motor interference between a precision grip-lift task and a working memory task. First, data from healthy participants were collected to calibrate the dual-task paradigm, and then the same paradigm was us to collect data in chronic stroke participants given us more insight on brain mechanism involved in dual-task and dexterous manipulation.

Chapter II describes our first experiment, during which 19 healthy participants performed a motor task in isolation or concurrently to an unrelated cognitive task. The motor task consisted of griping, lifting and holding an instrumented object with the pulp of the index and the thumb; while the cognitive task consisted of a complex visual-research and counting task. The data from both conditions (motor task only, dual-task), were compared to explore the potential Cognitive-Motor interference (CMi) of the cognitive task on motor performance. When a cognitive task is added, both the planning and the online control of the movement were disturbed. However, the cognitive task of this first experiment presented a certain number of limitations. The major limitation was that we did not know exactly which were the cognitive processes involved in the cognitive task and furthermore how they interacted with the grip-lift task. Thus, we changed the complex cognitive task with a well-known and more controlled working memory tasks, leading to our next experiment.

Chapter III describes our second experiment. Simultaneously to our previously described motor task, 37 healthy participants remembered a list of letters in alphabetical order, in a low load dual-task condition, or in random order, in a high load dual-task condition. By manipulating the cognitive load in the dual-task conditions, participants respectively recruited semantic and working memory. The data from the three conditions (motor only, motor + low load cognitive task and motor + high load cognitive task) were compared to 1) explore the impact of the cognitive load on the motor performance, 2) examine if a low and high cognitive load will induce the same perturbation of the motor performance, or, if the perturbation will increase with the increase of the cognitive load. Similarly to what we observed in the first experiment when disturbed by the cognitive task, both the planning and the online control of the movement were affected. Moreover, this CMi was scaled with the increase of the cognitive task load. The absence of age effect with the CMi was assumed to be a substantiation of the fine calibration of the cognitive task to each participant. The data from this experiment could serve as normative data for further experiments. This new dual-task paradigm can be used as a better suit tool to evaluate cognitive-motor interaction.

Chapter IV describes our third experiment. To explore the Cognitive-Motor interference after stroke, 11 chronic stroke participants performed the same experiment as the one described in Chapter III. The data from their affected and less-affected hand were compared with each other and with the dominant hand of healthy participants. The almost same CMi was found on time and force parameters of the grip-lift task, as in our previous studies, in both hands of chronic stroke participants with the strongest impact on the affected hand.

Finally, in Chapter V we discuss the results obtained from our previous studies, their limitations, their implications for evaluation and perspectives for future researches.

CHAPTER II. Cognitive-Motor Interference While Grasping, Lifting and Holding Objects

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II.1 Introduction

In everyday life, object manipulation is among the most common tasks we perform. Irrespective of the final goal, it generally involves grasping, lifting and holding objects. Despite its apparent easiness, grasping and loading an object involves a subtle interplay between predictive and feedback neural controls in order to generate a smooth vertical acceleration of the object (Johansson and Westling, 1984; Witney *et al.*, 2004; Flanagan, Bowman and Johansson, 2006). Visual cues provide information about most of the mechanical properties of the object (size, shape, etc.) that is useful to predict the forces required for successful manipulation (Gordon *et al.*, 1991). In addition, tactile input directly provides information about the mechanical interactions between our hands and objects (friction between skin and object, timing, magnitude and direction of fingertip forces) (Johansson and Westling, 1984, 1987; Johansson and Flanagan, 2009b).

Purposeful objects manipulation requires the ability to adapt in function of individual goals and environmental constraints (Grafton, 2010). Therefore, object manipulation cannot be considered as a series of rote repetitions with each movement exactly like the last, as the environment and the purpose of the movement vary considerably. Instead, object manipulation is a complex task requiring integration of sensory, motor and cognitive systems (Hesse and Deubel, 2011; McBride *et al.*, 2012). Most importantly, object manipulation in daily life is usually performed concurrently with other cognitive tasks such as attending a conversation or recalling a shopping list.

Dual-task paradigms have been used for many years to make inferences regarding the nature of the processing resources recruited during the performance of various tasks (Kahneman, 1973; Pashler, 1994). By examining the impact of a primary task on the performance of a secondary task, cognitive-motor dual-task paradigms have been used to explore the attentional demands of a motor task (Abernethy, 1988; Saling and Phillips, 2007). If an interaction is revealed, it can be assumed that both tasks compete for the same mental resources at some time during the execution of the two tasks (Pashler, 1994). Using such paradigms, previous studies have already shown that a concurrent cognitive task can interfere with the realization of upper limb movements (Creem and Proffitt, 2001; Glover *et al.*, 2004; Singhal, Culham and Goodale, 2007; Voelcker-Rehage, Stronge and Alberts, 2007; Enns and Liu, 2009; Li *et al.*, 2009; Hesse and Deubel, 2011; Spiegel *et al.*, 2012) Most of these studies reported that the early stages of the movement, i.e. the planning phase, can be affected by the cognitive task (Glover *et al.*, 2004; Liu, Chua and Enns, 2008; Enns and Liu, 2009; McIntosh, Mulroue and Brockmole, 2010; Hesse and Deubel, 2011; Hesse, Schenk and Deubel, 2012; Spiegel *et al.*, 2012). Depending on the nature of the cognitive task, some studies reported that the online control of movement during the execution phase is also affected (Hesse, Schenk and Deubel, 2012; Spiegel, Koester and Schack, 2013) whereas other studies failed to demonstrate such an effect (Creem and Proffitt, 2001; Enns and Liu, 2009; Spiegel *et al.*, 2012). The fact that different aspects of movement may involve specific aspects of cognition is highlighted by the results of Spiegel et al. (Spiegel, Koester and Schack, 2013), suggesting that spatial working memory interferes more with the execution of a movement than verbal working memory.

Only a few studies have focused on the effect of a cognitive task on the dynamics of precision grip movement (Voelcker-Rehage and Alberts, 2007; Li *et al.*, 2009) and, to our knowledge, no studies have explored the effects of an unrelated cognitive task on grip-lift-hold coordination. The aim of the present study was to use a dual-task interference paradigm, to characterize how performing such a cognitive task interferes with object manipulation in healthy individuals. Specifically, we applied a dual-task paradigm to assess cognitive-motor interferences while grasping, lifting and holding an object between the thumb and index finger, i.e. precision grip. The cognitive task consisted of a complex visual search combined with counting. The object manipulated by the participants was instrumented with sensors allowing an online recording of the force perpendicular to each contact surface (grip force) as well as the tangential force applied on the object (load force). This allowed us to characterize precisely the involvement of cognitive resources for each of the different temporal and dynamic aspects of precision grip. We found that the grip force applied onto the object, as well as the delay separating the initial contact of the fingers with the object and the onset of the load force applied onto the object, were increased in the dual-task condition, indicating that these two aspects of precision grip rely on cognitive processes. In contrast, other aspects of the precision grip – in particular the temporal coupling between grip and load forces – were not affected by the cognitive task. Taken together, our results suggest that assessment of dynamic and temporal parameters of the precision grip in dual-task paradigms could provide a more ecological and better-suited tool to characterize motor dysfunction in patients.

II.2. Methods

Participants

All participants provided written informed consent. The study was approved by the ethical committee of the Université catholique de Louvain, (B4032006615). Eighteen healthy naïve volunteers (undergraduate and graduate students of the university) took part in the experiment, (9 men and 9 women; mean age: 26 ± 3, range 22-29). None presented motor and/or cognitive deficits. All had normal or corrected to normal vision. According to the Edinburgh Oldfield Handedness Inventory (Oldfield, 1971), sixteen participants were right-handed and two were left-handed. Participants did not receive financial compensation for their participation.

Apparatus

The apparatus used for these experiments was a 275 g, 108 x 56 x 38 mm (height, width, and depth) mechanical assembly (Figure 2.1.) (fMRI-GLM, Arsalis, Belgium). The device was instrumented with full Wheatstone Bridges incorporating three strain gauges load sensors allowing to measure the force perpendicular to each contact surface (grip forces, GF left and GF right) as well as the tangential force applied on the object (load force, LF) (Dispa, Lejeune and Thonnard, 2013). It was calibrated up to a full scale of 30 N in each direction and demonstrated a maximum nonlinearity of 0.70 % for LF and 0.35 % for GF. The analogue signals were amplified, filtered with a Bessel 4-pole 150 Hz cut-off low-pass filter and sampled at 2000 Hz with a resolution of 16-bit. The resolution of the force measurements was 0.002 N for GF and 0.001 N for LF. The data was stored on a personal computer for offline analysis.

Visual and auditory stimuli were generated using Matlab 6.5 (The MathWorks Inc., USA) and the Cogent 2000 graphics toolbox (http://www.vislab.ucl.ac.uk/cogent_2000). Pictures and instructions were displayed on a 17 inch LCD monitor (AL1703sm, Acer Inc, USA) positioned approximately 1 m in front of the participant, using a 800x600 resolution and a 60 Hz refresh rate.

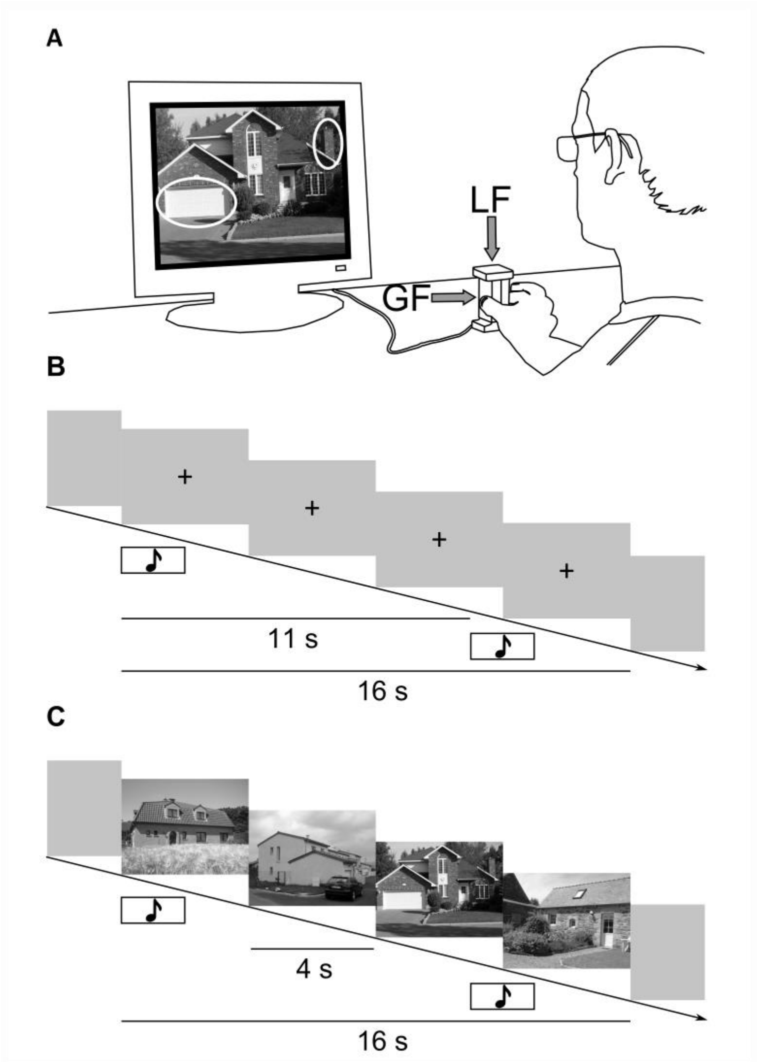

Figure 2.1. Experimental procedures. A. Participants were seated in front of a computer display and grasped the apparatus between the thumb and the index. The device was equipped with strain gauges measuring the grip force (GF) and load force (LF) developed during the experiment. B. In the “motor” condition (M), an auditory tone prompted the participant to grip, lift and maintain the apparatus approximately 5 cm above the table. After 11 s, a second auditory tone prompted the participant to put down the apparatus on the table and to reposition their hand at rest next to the apparatus. During the task, the participants fixated a cross displayed at the centre of the computer display. C. In the “motor + cognitive” condition (M+C), participants performed a visual search and counting task concomitant to the motor task. At the first tone, a colour photograph including a house was displayed on the computer screen. The photograph was changed every 4 s. A total of 4 pictures were shown in each trial. Participants were asked to count the number of pictures in which a chimney and a car, or a chimney and a garage could be identified. They reported their answer verbally at the end of each trial.

Experimental Design

Participants sat comfortably in a chair in front of a desk supporting the apparatus and LCD monitor. They were instructed to keep their non-dominant hand at rest, and their dominant hand around the apparatus (the thumb and index fingertips were positioned approximately 1 cm from the centre of the contact surfaces of the object) (Figure 2.1.). Before the beginning of each experimental session, participants had to wash their hands to reduce interindividual variability in finger skin friction. Each task was explained carefully. The experiment comprised two conditions. In the first condition (M), participants performed a motor task without any concomitant cognitive task. In the second condition (M+C), participants concomitantly performed the same motor task and a cognitive task.

The motor task was a grip-lift movement (Westling and Johansson, 1984). An auditory tone (2 s, 1100 Hz) prompted the participants to grip, lift and maintain the apparatus approximately 5 cm above the table. A second auditory tone (2 s, 700 Hz), occurring 11 s after the onset of the first, prompted the participants to put down the apparatus on the table and to reposition their hand at rest around to the apparatus. During the motor task, the participants were asked to fixate a black cross positioned at the centre of the screen (Figure 2.1.). Five seconds separated the end of each trial from the beginning of the following trial. This ensured that participants had enough time to reposition their hand next to the apparatus.

The cognitive task consisted of a visual search and counting task. At the first tone, a colour photograph including a house was displayed onto the computer screen. The photograph was changed every 4 s. A total of 4 pictures were shown in each trial. Participants had to recall the number of pictures in which a chimney and a car, or a chimney and a garage could be identified. Participants reported their answer verbally at the end of each trial. The visual search task lasted 16 seconds to ensure it covered the entire duration of the motor task including the grip, lift, hold and release phases, and to avoid any additional interference by the subject's verbal response to the cognitive task. Each picture was shown only once throughout the experimental session. Half of the presented pictures were targets (i.e. pictures showing a chimney and a car or a chimney and a garage). The order of the pictures was the same for each participant.

In both the M and the M+C conditions, the procedure was repeated ten times. Importantly, because participants were required to fixate the computer screen in both conditions, visual feedback related to the hand/object position was identical in the two conditions. Participants were given the opportunity to practice each condition (ten consecutive trials for each condition). The order of the conditions (M and M+C) was counterbalanced between participants.

Furthermore, for each participant, the skin-apparatus coefficient of static friction was measured three times: before the practice trials, before the recording trials and after the recording trials, in a series of eight lift-and-drop manoeuvres during which the participant lifted and held the instrument stationary, then gradually released the grip until the object slipped due to gravity (Westling and Johansson, 1984).

Data analysis

Forces were analysed using Matlab 7.5 (The MathWorks, Inc., USA). Signals were low-pass filtered using a Butterworth filter (cut-off: 15 Hz; slope: 2dB). Typical GF and LF traces are shown in Figure 2.2. These traces can be decomposed into distinct phases (Johansson and Westling, 1984): (a) the preload phase, defined as the time between initial contact of the fingers with the apparatus and onset of the load force, (b) the load phase during which both GF and LF increase up to the point where LF equals the weight of the apparatus (2.75 N), i.e. the point where the apparatus is lifted from the table, (c) the lift phase corresponding to the time interval before stabilisation of the apparatus above the table and (d) the hold phase corresponding to the time interval during which the apparatus remains stable above the table. In addition to the duration of these phases, the following parameters were compared across conditions: the GF at onset of the load force (LF > 0.1 N) and at lift off which provides information about the grip force applied at the very early stage of the movement, i.e. at the beginning and the end of the load phase, the maximum GF; and the mean and standard deviation of GF during the hold phase.

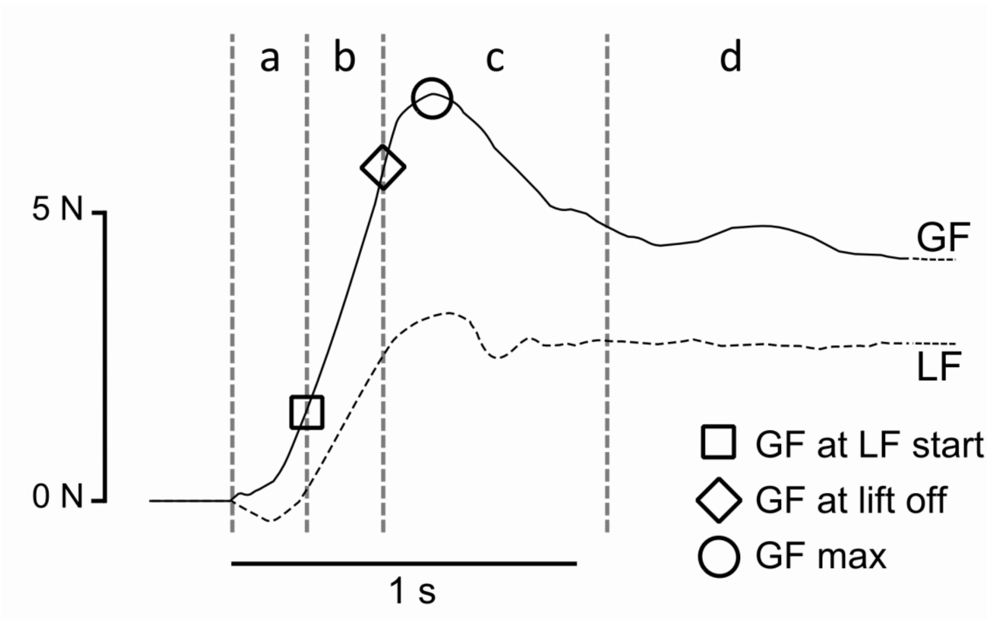

Figure 2.2. Time course of grip force (GF: continuous waveform) and load force (LF: dotted waveform) during the grip and hold task. Several measures were extracted from these waveforms. The preload phase (a) corresponds to the duration separating the first contact of one finger on the apparatus and the onset of a positive load force (LF). The load phase (b) corresponds to the time during which a parallel increase of GF and LF is observed. The lift phase (c) corresponds to the time during which the apparatus is raised and stabilized. The hold phase (d) corresponds to the time during which the object is maintained in a stable position. GF at LF start corresponds to the value of GF at the beginning of the load phase. GF at lift off corresponds to the value of GF when LF equals the weight of the apparatus, i.e. when the apparatus begins lift off. GF max corresponds to the maximum values of GF. Values are in Newton (N) and second (s).

For each lift-and-drop manoeuvres, the static coefficient of friction (CF) was estimated as half the LF/GF ratio at slip onset (Johansson and Westling, 1984):

$$CF = LFat\ slip / 2GFat\ slip$$

This was used to compute the safety margin (SM) providing information on the excess of grip force applied onto the object. It corresponds to the ratio of two forces and therefore has no unit.

$$SM = (GFhold - GFat\ slip) / GFhold$$

with $GFat\ slip = LFhold / 2CF$

Finally, the temporal coupling of load and grip force was assessed using a cross-correlation analysis (Duque *et al.*, 2003) between the first derivative of LF (dLF/dt) and the first derivative of GF (dGF/dt) in the time interval separating the first contact of one finger on the apparatus and GF max. This measure involves progressively sliding one waveform past the other and computing the correlation coefficient between the time-shifted signals. The cross-correlation function peaks at time lags where the two waveforms are best aligned. The analysis thus provides two values: (a) the time lag at maximum correlation which provides an estimate of the time lag between the two signals and (b) the maximum coefficient of correlation which provides an estimate of the similarity between the two time courses. To assess the effect of the cognitive task on the asynchrony between GF and LF, we computed the absolute value of time lags.

Statistical analyses

The measures obtained in each of the two conditions (M vs. M+C) were compared using paired t-tests when they followed a normal distribution and using a Wilcoxon signed rank test when they did not (Sigma Stat 3.5, SPSS Inc., USA). Normality was tested using the Kolmogorov-Smirnov test. To address the problem of multiple comparisons, the significance level was corrected using a False Discovery Rate (FDR) procedure (Benjamini and Hochberg, 1995). A One-Way Repeated Measure Analysis of Variance on ranks was performed to test values of CF obtained at the different time points (before the practice trials, before the recording trials and after the recording trials).

II.3. Results

The cognitive task was correctly performed by each participant (89 ± 9% of correct answers; mean ± standard deviation).

Table 2.1 presents the group-level mean and standard deviation of each measured dynamic and temporal parameters of the grip-lift task performed in the M and M+C conditions, as well as the results of the comparison between the two conditions.

Temporal Parameters	M Mean (SD)	M + C Mean (SD)	**M vs M + C** *t*- test	*p* -value	
Preload Phase (ms)	230 (91)	285 (104)	2.88	0.010	*
Load Phase (ms)	214 (51)	209 (48)	0.40	0.691	
Lift Phase (ms)	688 (105)	661 (75)	1.54	0.141	
CrossCorrelation Coefficient	0.92 (0.03)	0.91 (0.03)	1.64	0.120	
Absolute Time Shift (ms)	26 (17)	17 (11)	0.81 1	0.442	

Dynamic Parameters	M Mean (SD)	M + C Mean (SD)	*t*- test	*p* -value	
GF at LF start (N)	1.28 (0.76)	1.39 (0.74)	0.15 1	0.899	
GF at lift off (N)	5.72 (0.82)	6.28 (1.05)	2.30	0.035	*
GF max (N)	6.57 (0.83)	7.18 (1.01)	3.09	0.007	*
GF hold (N)	4.56 (0.56)	5.07 (0.61)	2.97	0.009	*
Safety Margin	0.53 (0.06)	0.58 (0.05)	3.47	0.003	*

Table 2.1. Mean and standard deviation (SD) of Temporal and Dynamic parameters of the M and M+C conditions. Significant results ($p < .05$; corrected using the Benjamini & Hochberg False Discovery Rate procedure (Benjamini and Hochberg, 1995)), are highlighted with an asterisk. “1” indicates when a Signed Rank test was performed.

Temporal parameters

The preload phase was significantly lengthened in the M+C condition ($t(17)=2.88$; $p=0.010$). On average, it was 55 ± 80 ms longer in the M+C condition as compared to the M condition. In contrast, the concurrent cognitive task did not interfere with the duration of the load phase ($t(17)=0.40$; $p=0.691$) and the duration of the lift phase ($t(17)=1.54$; $p=0.141$).

The cross-correlation function did not reveal any change in the temporal coupling between GF and LF The average absolute time lag between GF and LF was 26 ± 17 ms in M condition and 17 ± 11 ms in the M+C condition This difference was not significant (z=0.81; p=0.442). The average of maximum cross-correlation coefficients was 0.92 ± 0.03 in the M condition and 0.91 ± 0.03 in the M+C condition. This difference was not significant (t(17)=1.64; p=0.141).

Dynamic parameters

GF max was significantly increased in the M+C condition as compared to the M condition (t(17)=3.09; p=0.007). On average, GF max was increased by +0.61 ± 0.84 N in the M+C condition A significant increase of GF was also observed during the hold phase (+0.51 ± 0.74 N; t(17)=2.97; p=0.009). GF was increased at lift off (+0.55 ± 1.02 N; t(17)=2.30; p=0.035), but this difference was not significant after FDR correction for multiple comparisons. In contrast, GF at the beginning of the load phase (GF at LF start) and the standard deviation of GF during the hold phase were not significantly different in the M and M+C conditions (z=0.15; p=0.899 and t(17)=0.31; p=0.759).

Values of CF did not follow a normal distribution; a Kruskal-Wallis one-way repeated measure analysis of variance on ranks was performed. The differences among the values of CF were not significant (h(2)=0.71; p=0.703). Thus we assumed that participants showed a similar CF in all conditions.

The SM, which depended on the GF exerted during the hold phase, was significantly different in the M and M+C conditions (t(17)=3.47; p=0.003). On average, participants increased their safety margin from 0.53 ± 0.06 in the M condition to 0.58 ± 0.05 in the M+C condition.

II.4. Discussion

The objective of this study was to investigate cognitive-motor interference by assessing the interactions between a precision handgrip motor task and an unrelated cognitive task. This allowed us to examine the involvement of high-level cognitive resources in the performance of common manual behaviour. In the dual-task condition, we found a significant increase in the duration of the preload phase, as well as a significant increase in the grip force during the hold phase. In contrast, the other aspects of the precision grip, such as the temporal coupling between grip and load forces were not affected by the cognitive task.

The preload phase was significantly increased when performing the concurrent cognitive task. The preload phase is critical to encoding somatosensory input generated by the initial contact with the object. It has been shown by Westling and Johansson (Westling and Johansson, 1987) that, during the preload phase, fast adapting and slowly adapting type 1 mechanoreceptors encode afferent information that is decisive for the release of the motor commands accounting for the load phase. It seems obvious that, during the preload phase, the central nervous system needs information indicating reliable contact before releasing the muscle commands leading to the load phase. Previous studies have shown that the duration of the preload phase is increased in very young children (Forssberg *et al.*, 1991), in older adults (Diermayr, McIsaac and Gordon, 2011), in children and adults with hemiplegia (Duque *et al.*, 2003; McDonnell *et al.*, 2005) and in healthy adults following repetitive transcranial magnetic stimulation of the primary somatosensory cortex (Schabrun, Ridding and Miles, 2008). In most of these studies, it seems likely that the increased duration of the preload phase results from altered cortical processing of the sensory signals generated by the contact of the fingers with the object and/or integration of that information into the movement plan. Our finding that the duration of the preload phase is increased in the dual-task condition implies that at least some of these processes involve cognitive resources and, hence, correspond to controlled processes rather than purely automatic processes. One possibility is that the increased duration of the preload phase in the dual-task condition is due to the fact that cortical processing of the somatosensory input generated by the contact of the finger with the object is modulated by the focus of selective attention, or by the availability of working memory resources. This view is also supported by the results of previous studies showing that movement planning requires working memory resources and can interfere with concurrent cognitive processing (Glover *et al.*, 2004; Liu, Chua and Enns, 2008; Enns and Liu, 2009; McIntosh, Mulroue and Brockmole, 2010; Hesse and Deubel, 2011; Hesse, Schenk and Deubel, 2012; Spiegel *et al.*, 2012).

Another explanation to consider is that, in the dual-task condition, the increased duration of the preload phase was due to the fact that the participants already increase grip force during this phase of the movement. However, this hypothesis can be rejected as the grip force at the beginning of the load phase (GF at LF start) was not increased in the M+C condition.

The maximum grip force (GF max) and the grip force during the holding phase (GF hold) were the two other factors significantly increased during the dual-task condition. One possible explanation to the increased grip force is that participants anticipated the interference of the concurrent cognitive task by increasing the safety margin and, thereby, reducing the risk of letting the object slips because of less optimal planning and/or fine-tuning of the grip force.

During the hold phase, the grip force is thought to be adjusted through reactive mechanisms relying on tactile feedback (Johansson and Westling, 1984). In a highly economical fashion, the grip force would be maintained just above the force under which the object would slip. This is supported by the fact that, when peripheral sensory information is impaired, the grip force is increased because the adjustment of grip force is no longer optimal, as shown in healthy participants with local anaesthesia of the index and thumb (Augurelle *et al.*, 2003), in older adults (Diermayr, McIsaac and Gordon, 2010), under mental stress in microgravity and hypergravity environments (Augurelle *et al.*, 2002) and in participants with peripheral nerve lesions (Thonnard *et al.*, 1997; Afifi, Santello and Johnston, 2012). In the present study, we observed a similar increase of grip force in the dual-task condition, thus suggesting that participants adopted a similar behaviour to compensate the fact that the cognitive task interfered with the fine adjustment of grip force during the hold phase. Few studies have examined the impact of attentional disorders on the performance of a precision grip-lift task. Pereira et al. (Pereira, Eliasson and Forssberg, 2000; Pereira *et al.*, 2001) showed that children with attention-deficit–hyperactivity disorder (ADHD), and children with deficits in attention motor control and perception (DAMP), have deficient control of fingertip forces during precision grip-lift movement. They attributed this impairment to a general deficit of working memory function. Our findings provide further evidence that the fine-tuning of grip force during the hold phase involves cortical processes that are dependent on the cognitive resources required to perform an unrelated cognitive task involving selective attention and/or working memory function (Spiegel, Koester and Schack, 2013).

One possible explanation for the increase in grip force observed during the dual-task condition could be that this increase compensated a reduction in the coefficient of friction between the fingertips and the manipulated object. Indeed, the difficulty of the dual-task could have induced an autonomic response leading to a change in skin fingertip moistness, a factor known to crucially determine the coefficient of friction (Bleyenheuft, Lefèvre and Thonnard, 2009; André, Lefèvre and Thonnard, 2010). However, this was not the case, as we did not observe any significant difference in the coefficient of friction across trials.

Contrasting with the effect of the cognitive task on the preload phase and grip force, there was no significant difference in the temporal coupling of grip and load forces, as assessed by the cross-correlation between the two measures (Flanagan and Tresilian, 1994). This suggests that this coupling may rely on automatic processes that are less dependent or do not involve cognitive resources.

Although participants were asked to focus their gaze on the computer screen in both conditions, actual eye movements were not controlled. As fixation can affect reaching and grasping behaviour, this limitation of the present study could be addressed in future studies, using eye-tracking methods to monitor eye gaze in the different conditions.

Altogether our findings show that mental resources are required for both the planning and the online control of upper limb movement (Hesse, Schenk and Deubel, 2012; Spiegel, Koester and Schack, 2013). Using a similar dual-task paradigm, future studies should examine the influence of a cognitive task on the different aspects of precision grip in participants presenting with a peripheral or central lesion of the nervous system affecting the transmission and processing of sensory input and motor output (e.g. sensory and motor impairment following stroke and/or peripheral neuropathy). Indeed, it may be that following such a lesion, precision grip is even more dependent on cognitive resources. This is of particular importance as previous studies have largely failed to demonstrate decisive changes in precision grip following specific rehabilitation procedures, although patients often report a subjective improvement of their ability to conduct daily-life activities involving the manipulation of objects (Dispa, Lejeune and Thonnard, 2013). Therefore, it would be of interest to examine whether these rehabilitation procedures reduce the impact of a concurrent cognitive task on the precision grip, which would suggest that the rehabilitation reduced the number of cognitive resources required for object manipulation (Voelcker-Rehage and Alberts, 2007; Kimberley *et al.*, 2008). In other words, studying precision grip in the context of a concurrent cognitive task may constitute a more ecological way to study motor function, which could be especially useful for the clinical evaluation of patients and the assessment of treatment efficacy.

CHAPTER III. Mind Your Grip! Even Usual Dexterous Manipulation Requires High-Level Cognition.

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III.1. Introduction

Dexterous manipulation is probably the most habitual way we interact with objects of the environment. Precision grip movements, besides their apparent simplicity, rely on complex anticipatory and online controls on the movement (Nowak and Hermsdörfer, 2004; Witney et al., 2004; Westling and Johansson, 1984). The great majority of studies aiming at understanding the neural mechanisms underlying dexterous manipulation have focused on motor tasks performed in isolation. Similarly, assessment of motor dysfunction in patients, or assessment of changes in motor function induced, for example, by chronic stroke rehabilitation, often rely on the performance of isolated motor tasks. Yet, recent studies have shown that performing a higher-order cognitive task may interfere with the realization of upper limb movements (Guillery et al., 2013; Spiegel et al., 2013; Maes et al., 2015; Bumsuk et al., 2014; Li et al., 2009; Voelcker-Rehage and Alberts, 2007; Voelcker-Rehage et al., 2007; Temprado et al., 2015) and, in our daily life, object manipulation is most-often performed concomitantly to other tasks involving higher-order cognitive functions such as manipulating a glass while having a conversation, or interacting with a computer or smartphone. Therefore, habitual dexterous manipulation may not only rely entirely on automatic processes and, instead, may require higher-order cognitive functions.

In a recent study, we aimed to test this hypothesis by means of a dual-task paradigm combining a simple object manipulation with a high-level cognitive task (Guillery et al., 2013). The experimental procedure consisted of instructing participants to perform two tasks simultaneously or in isolation in order to assess how the two tasks impact each other when performed in combination. We postulated that if the performance of one or both tasks was reduced in the dual-task condition, this would be an indication that the two tasks compete for shared processing resources (Abernethy, 1988). The motor task consisted in manipulating an apparatus equipped with force sensors to measure the forces applied while gripping, lifting and maintaining the object for a short duration. The cognitive task consisted of performing a complex visual search and counting task. As compared to when the motor task was performed in isolation, when participants performed the dual task, they took more time to assess the physical properties of the object during the preload phase, and applied more force on it (Guillery et al., 2013). This observation supports the view that simple object manipulation is not a strictly automatic behaviour and, instead, that its achievement involves higher-order cognitive functions. However, the cognitive task did not allow determining which higher-order processes were involved in the observed interference. Most importantly, the visual search and counting task involved also motor activities such as head and eye movements. Therefore, the differences observed in the dual-task condition could have resulted from the competition of resources specifically involved in motor control.

In the present study, we explore further the involvement of high-level cognitive processes on dexterous manipulation by combining a motor grip-lift task with a working memory task. Besides its role in short-term storage of sensory inputs (Aubin et al., 2007), working memory is also regarded as an executive function involved in monitoring control over information processing (Hegarty et al., 2000) such as prioritizing the processing of relevant target stimuli from interfering distracters (Lavie and De Fockert, 2005). For instance, in a dual-task combining an attentional task with a working memory task, De Fockert et al. showed that the performance of the attentional task was decreased when working memory abilities were captured by a second unrelated task (de Fockert et al., 2001) Conversely, the ability to control distraction is increased when the participants are encouraged to use working memory abilities to perform the attentional task (Legrain et al., 2013, 2011a, 2011b).

Participants were requested to perform the grip-lift motor task either in isolation or in combination with one of two cognitive tasks contrasting only by how they recruited working memory. Because none of the two cognitive tasks involved any aspect related to motor control, and because they contrasted only by their load on working memory functions, showing an effect of the cognitive tasks on the performance of the grip-lift motor task would constitute conclusive evidence that simple object manipulation involves higher-order cognitive functions. We also tested whether cognitive involvement in the motor task was age-dependent.

III.2. Methods

Participants

Thirty-seven healthy volunteers took part in the experiment (19 men and 18 women, mean age: 45 ± 19, range: 21-78). Participants were assigned to one out of three groups according to their age: Young (from 20 to 30 years old: n = 13, mean age = 26 ± 2), Middle Age (from 30 to 60: n = 12, mean age = 43 ± 9) and Older (from 60 and more: n = 12, 68 ± 6). All participants had normal or corrected to normal vision and no history of neurological disease. Participants did not receive financial compensation for their participation and they all provided written informed consent. The study was approved by the local ethics committee.

Pre-experimental assessment

Before the actual experiment, the cognitive abilities of the participants were tested with the Mini-Mental State Examination (MMSE) (Folstein et al., 1975) (Appendix A). Handedness was tested with the Edinburgh Oldfield Handedness Inventory (Oldfield, 1971). Most importantly, the pre-experimental evaluation included an assessment of memory span for letters, i.e. the capacity of working memory to rehearse series of letters for their immediate use (Conway et al., 2005). This was achieved in order to individually adjust the working memory task of the experimental session to the abilities of the participant and, thereby, avoid using series of items beyond working memory capacity. The assessment of working memory span was similar to the standard Digit Span subtest of the Wechsler Memory Scale (Wechsler, 1981). Participants were asked to memorize a series of consonant letters presented on a screen for 2.25s and to repeat the entire series in the correct order immediately after they disappeared from the screen. Vowels were not used in order to prevent participants from chunking the letters into pronounceable words or pseudo-words. Meaningful sequences such as acronyms were also avoided. Trials started with a series of three letters. After each repetition of two successful trials, one item was added to the series. Otherwise, the procedure was stopped. The length of the longest series a participant could repeat successfully was considered as his memory span of letters.

Stimuli and Apparatus

The apparatus used to perform the grip-lift task was a 275 g, 108 x 56 x 38 mm (height, width, and depth) mechanical assembly (fMRI-GLM, Arsalis, Belgium). The device was instrumented with full Wheatstone Bridges incorporating three strain gauges load sensors allowing to measure the force perpendicular to each contact surface (grip forces, GF left and GF right) as well as the tangential force applied on the object (load force, LF) (Guillery et al., 2013). It was calibrated up to a full scale of 30 N in each direction and demonstrated a maximum nonlinearity of 0.70 % for LF and 0.35 % for GF. The analogue signals were amplified, filtered with a Bessel 4-pole 150 Hz low-pass filter and sampled at 2000 Hz with a resolution of 16 bits. The resolution of the force measurements was 0.002 N for GF and 0.001 N for LF. The data was stored on a personal computer for offline analysis.

Visual and auditory stimuli were generated using Matlab 7 (The MathWorks Inc., MA) and the Cogent 2000 graphics toolbox (http://www.vislab.ucl.ac.uk/cogent_2000). Visual material and instructions were displayed on a 17 inch LCD monitor (AL1703sm, Acer, Taiwan) positioned approximately 1 m in front of the participant, using a 800x600 resolution and a 60 Hz refresh rate. The visual stimuli consisted of a list of consonants, a consonant or a cross displayed at the centre of the screen in capital letters (font: Tahoma, size: 80). They encompassed approximately 3° of visual angle. The auditory stimulus was a 725 Hz tone lasting 0.19 s.

Procedure

Participants sat comfortably in a chair in front of a desk supporting the apparatus and LCD monitor. During the experiment, they were instructed to keep their non-dominant hand at rest, and their dominant hand around the apparatus. Instructions about the task were given verbally. They were asked to perform the different tasks under three conditions. In the first condition (M), participants performed a motor task without any concomitant cognitive task. In the second and third conditions, participants concomitantly performed the same motor task with either a low-load cognitive task (M+L) or a high-load cognitive task (M+H). They were asked to perform the cognitive tasks as fast and as accurately as possible. In the dual-task conditions, they were asked not to give priority to the motor or to the cognitive tasks. Participants were given the opportunity to practice the tasks before the experiment in five consecutive trials for each condition. Next, participants performed six experimental blocks of 8 trials each, two blocks per condition. The order of the conditions was counterbalanced across participants.

The motor task (M) consisted in a grip-lift movement (Figure 3.1.A) (Westling and Johansson, 1984; Guillery et al., 2013). The trial started with the participants fixating a black cross positioned at the centre of the screen. After 4.25s an auditory tone prompted the participants to grip, lift and maintain the apparatus approximately 10 cm above the table. A second auditory tone, occurring 8s after the onset of the first, prompted the participants to put down the apparatus on the table and to reposition their hand at rest around the apparatus. Five seconds separated the end of each trial from the beginning of the following trial. This ensured that participants had enough time to reposition their hand next to the apparatus (Figure 3.1.B).

In the M+L and M+H conditions, each trial started with the presentation of a memory set consisting of a list of letters on the screen. The letters were chosen among the following list of letters: J, K, L, M, N, P, Q, R, S, T, V. The length of the set was adapted individually to match the length of the memory span for letters assessed before the beginning of the experiment. The letters were shown for 2.25s and then replaced by a fixation cross (Figure 3.1.B). Such as in the M condition, an auditory tone was presented 4.25s after trial onset, prompting the participant to perform the motor task. Then, after 8s, the second auditory tone occurred, prompting the participant to put down the apparatus on the table. Finally, 2.75s after the second auditory tone, one single letter belonging to the list was presented for 1s, and participants were instructed to report verbally which letter followed that letter in the memory set presented at the beginning of the trial.

In the M+L condition, the letters of the memory set were presented in alphabetic order (e.g. JKLMN). Hence, participants could rely simply on their semantic knowledge about the Latin alphabet. In the M+H condition, the letters were presented in a pseudo-random non-alphabetic order, and the same order was never repeated twice. Hence, performing the task required participants to store and rehearse in working memory the complete list of letters in their correct order while they performed the motor task.

Coefficient of friction

The amount of grip force required to lift the object without letting it slip through the fingers is dependent on the coefficient of friction between the fingers and the object surface. Therefore, before and after the experiment, we estimated the skin-apparatus coefficient of static friction (CF) by asking participants to perform a series of 8 lift-and-drop manoeuvers with the apparatus. The participants lifted and held the instrument stationary, then gradually released the grip until the object slipped due to gravity (Johansson and Westling, 1984). For each lift-and-drop manoeuvres, the static coefficient of friction (CF) was estimated as half the LF/GF ratio at slip onset (Johansson and Westling, 1984).

Measures

The performance of the cognitive tasks was assessed by computing the percentage of correct answers, i.e. the percentage of trials for which the correct letter of the memory set was reported.

Forces (in N) were analysed using Matlab 7.5 (The MathWorks, Inc., MA). Signals were low-pass filtered using a Butterworth filter (cutoff: 15 Hz; slope: 2dB). Typical GF and LF traces are shown in Figure 3.2 (Guillery et al., 2013). In the M+L and M+H conditions, trials for which the participants did not provide the correct answer in the cognitive task were rejected from further analyses.

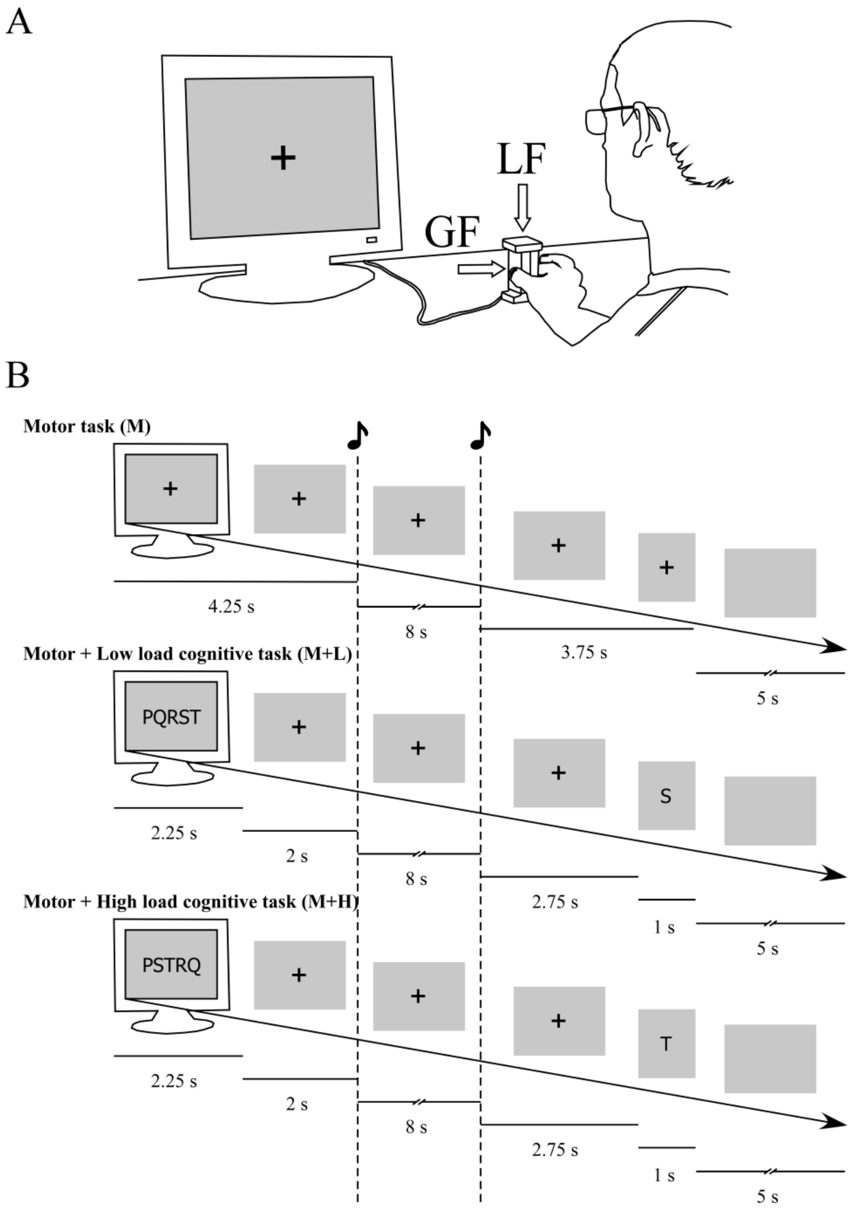

Figure 3.1. Experimental procedures and Time course of trials in different conditions. A. Participants were seated in front of a computer display and grasped the apparatus between the thumb and the index. The device was equipped with strain gauges which allowed measuring the grip force (GF) and load force (LF) developed during the experiment. They had to keep their eyes on the fixation cross when no other stimulus was displayed.

B. In the Motor condition (M), an auditory tone prompted the participant to grip, lift and hold the object approximately 5 cm above the table. After 8 s, a second auditory tone prompted the participant to put down the object on the table and to reposition their hand at rest next to the object. In the Motor + Cognitive conditions, a list of letters appeared at trial onset. Participants were requested to remember this list of letters, whose length was adapted to their individual memory span. The list was in alphabetical order in the Motor + Low-load cognitive condition (M+L) and in a randomized order in the Motor + High-load cognitive condition (M+H). Participants performed the grip-lift-hold task while maintaining the list of letters in working memory. After the motor task, a random letter from the initial memory set reappeared, and participants were instructed to report verbally which letter of the memory set was presented after that letter.

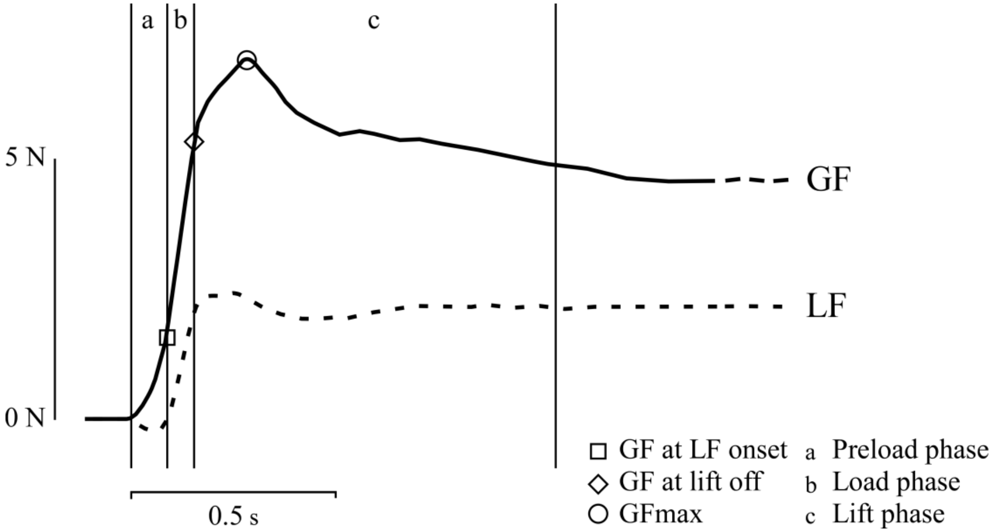

Figure 3.2. Time course of grip force (continuous trace) and load force (dotted trace) during a typical trial of the grip-lift-hold task. The Preload phase (a) corresponds to the time separating the first contact of one finger on the apparatus and the onset of a positive load force (LF). The Load phase (b) corresponds to the time during which a parallel increase of grip force (GF) and LF is observed. The Lift phase (c) corresponds to the time during which the apparatus is raised and stabilized over the table. Several force measures were extracted from the waveforms. The GF at LF onset corresponds to the value of GF at the beginning of the Load phase. The GF at lift-off corresponds to the value of GF when LF equals the weight of the apparatus, i.e. when the apparatus begins its lift-off. The GF max corresponds to the maximum value of GF. Values are in Newton (N) and second (s).

The time course of the grip-lift movement can be decomposed into series of distinct phases (in ms): the Preload phase, the Load phase, the Lift phase and the Hold phase (see Guillery et al., 2013) for more details about these measures). The Preload phase is defined as the time between initial contact of the fingers with the apparatus and the onset of the load force (LF > 0.1 N), i.e. when participants start to apply an upward vertical force to load the object. The Load phase is defined as the time during which both GF and LF increase up to the instant when LF equals the weight of the apparatus (2.75 N), i.e. the instant when the apparatus is actually lifted from the table. The Lift phase is defined as the time interval during which the apparatus is lifted upwards until stabilisation above the table. Finally, the Hold phase is defined as the time interval during which the apparatus remains stable above the table.

In addition to assessing the duration of these phases, the GF and LF forces measured at different time points were used to summarise the performance of the motor task: GF at LF onset, GF at lift off, GF max and GF hold. The GF at LF onset and the GF at lift off provide information about the grip force applied at the very early stage of the movement, i.e. at the beginning and the end of the Load phase, respectively. The GF max corresponds to the maximum grip force applied during the trial, and usually occurs at the end of the Lift phase. The GF hold is computed by averaging the GF during the Hold phase, and provides information about how the GF is maintained while the apparatus remains stable above the table. The GF hold was also used to compute the Safety Margin (SM). The SM provides information on the excess of grip force applied onto the object to prevent it from slipping through the fingers. It is expressed as the ratio between the excess of grip force while holding the object (GF hold – GF at slip), divided by the GF hold.

Finally, to assess the effect of the cognitive task on the temporal coupling of load and grip forces, a cross-correlation analysis was performed using the first derivative of LF (dLF/dt) and the first derivative of GF (dGF/dt), in the time interval separating the first contact with the apparatus and the GF max (Duque et al., 2003). The time lag at maximum correlation provides an estimate of the time lag between the two signals and the maximum coefficient of correlation provides an estimate of the similarity between the two time courses. We computed the absolute value of time lags.

Statistical analyses

Statistical analyses were performed using SPSS 21 (IBM, NY). For all analyses, the significance level was set at $p < 0.05$.

The memory span of letters was compared between the different groups using an analysis of variance (ANOVA) with 'age' (young vs. middle aged vs. older) as group factors.

The impact of the cognitive tasks on the performance of the motor task (M vs. M+L vs. M+H) was assessed by comparing the different temporal and force measures obtained from the grip-lift task using an ANOVA with 'condition' as within-subject factor and 'age' as between-subject factors. Values of CF obtained before and after the experiment were compared using the same ANOVA. Greenhouse-Geisser corrections for degrees of freedom and contrasts analyses with Student t-tests were used when necessary. Effect sizes were estimated by means of partial eta squared and sensitivities were estimated by observed power.

Finally, to compare the time courses of GF during the grip-lift task performed in the different conditions, single-subject average waveforms of GF obtained for each of the three conditions, aligned relative to lift off, were compared using a point-by-point ANOVA with 'condition' as within-subject factor and 'age' as between-subject factors. This method allowed identifying the time intervals where the GF traces showed a significant main effect of 'condition' (M vs. M+L vs. M+H), 'age', or a significant interaction between the three factors. When significant, the same method was applied to compare the different average waveforms of GF of each condition pairwise, using point-by-point t-tests.

III.3. Results

Participants

According to the Edinburgh Oldfield Handedness Inventory (Oldfield, 1971), 34 participants were right-handed and three participants were left-handed. Their score at the MMSE was 29.97 ± 0.16 (mean ± standard deviation). This indicates the absence of any blatant cognitive deficit. Statistical analyses of the memory span of letters did not reveal any significant difference between age groups (all $F<0$; all $p>0.7$). The mean span of letters was 7 ± 1 in each group. Consequently, the mean length of letter strings used in the M+L and M+H tasks was identical in all groups.

Time Parameters	M	M + L	M + H	Repeated measure ANOVA				
	mean (SD)	mean (SD)	mean (SD)	*F*	df	*p*-value	η^2	Observed Power
Preload phase (ms)	106 (46)	129 (60)	126 (56)	7.95	(2,62)	<0.001	0.20	0.95
Load phase (ms)	128 (35)	120 (27)	106 (22)	13.68	(1.7,44.8)	<0.001	0.31	0.99
Lift phase (ms)	851 (44)	863(37)	871 (39)	4.73	(1.6,50.7)	0.02	0.13	0.71
Cross-Correlation Coefficient	0.81 (0.07)	0.82 (0.06)	0.82 (0.06)	1.97	(2,62)	0.15	0.06	0.39
Absolute Time-Lag (ms)	10.63 (8.09)	9.30 (8.61)	8.78 (7.13)	3.87	(2,62)	0.03	0.11	0.68
Force Parameters	**M**	**M + L**	**M + H**					
	mean (SD)	mean (SD)	mean (SD)	*F*	df	*p*-value	η^2	Observed Power
GF at LF start (N)	1.60 (1.52)	1.60 (1.59)	1.79 (1.78)	1.90	(1.8,56.2)	0.16	0.06	0.36
GF at lift off (N)	5.27 (2.49)	5.68 (2.77)	6.17 (2.93)	8.94	(2,62)	<0.001	0.22	0.97
GFmax (N)	6.67 (2.70)	7.78 (3.68)	8.59 (4.00)	13.99	(2,62)	<0.001	0.31	1.00
GFhold (N)	4.48 (1.99)	5.17 (2.96)	5.80 (2.95)	11.44	(15.4,59.2)	<0.001	0.27	0.99
Safety Margin	0.52 (0.21)	0.58 (0.17)	0.63 (0.14)	21.42	(2,62)	<0.001	0.41	1.00

Table 3.1. Mean and standard deviation (SD) of the parameters of the grip-lift task performed in the M, M+L and M+H conditions; and main effects of condition on these parameters. Effect sizes were estimated by means of partial eta squared values and sensitivity were estimated by observed power. Values are in Newton (N) and second (ms).

Performance of the cognitive task

The participants provided the correct answer to the cognitive task in 98 ± 5 % of trials in the M+L condition and 77 ± 13 % of trials in the M+H condition. The difference in the percentage of errors between the M+L and M+H conditions was significant ($F(1,6)=47.7$; $p<0.001$). The performances were not affected by 'age' (all $F<0$; all $p>0.6$).

Performance of the motor task

Table 3.1. presents the group-level mean and standard deviation of each measured parameter of the grip-lift task performed in the M, M+L and M+H conditions, and the main effects of the factor 'condition'. Figure 3.3. illustrates the pairwise comparisons between the three conditions.

Time parameters

There was a significant main effect of 'condition' on the duration of the Preload phase ($F(2,62)=7.95$; $p<0.001$), the duration of the Load phase ($F(1.7,44.8)=13.68$; $p<0.001$), and the duration of the Lift phase ($F(1.6,50.7)=4.73$; $p<0.02$), indicating that the duration of the different phases of the grip-lift task were affected by the cognitive tasks. Post hoc comparisons showed that, as compared to the M condition, the Preload phase was significantly longer in the M+L condition (mean Δt = 23 ms; $t(36)=3.73$; $p=0.001$) and the M+H condition (mean Δt = 20 ms; $t(36)=3.25$; $p=0.003$). There was no difference in the duration of the Preload Phase between the M+L and M+H conditions ($t(36)=0.48$; $p=0.63$). Conversely, the duration of the Load phase was significantly shorter in the M+H condition as compared to the M condition (mean Δt = 22 ms; $t(36)=5.08$; $p<0.001$) and significantly shorter in the M+H condition as compared to the M+L condition (mean Δt = 14 ms; $t(36)=5.95$; $p<0.001$). There was no significant difference between the M and M+L conditions ($t(36)=1.75$; $p=0.09$). The duration of the Lift phase was significantly greater in the M+H condition as compared to the M condition (mean Δt = 20 ms; $t(36)=2.21$; $p=0.03$), but there was no significant difference between the M and M+L conditions ($t(36)=1.95$; $p=0.06$) and between the M+L and M+H conditions (*t*(36)=1.35; *p*=0.19). Regarding the group factors, there was a significant main effect of ‘age’ on the duration of the Preload phase (*f*(2,31)=3.78, *p*=0.03), whose duration tended to be significantly shorter in the middle age group as compared to the older group (mean Δt = 52 ms; *t*(16.8)=2.07; *p*=0.05). There was no significant interaction between this factor and the factor ‘condition’ (all *F*<1.4; all *p*>0.15).

Force parameters

The cognitive tasks also exerted an effect on the grip-force applied while performing the motor task. There was a significant main effect of ‘condition’ on the GF at lift-off (*F*(2,62)=8.94; *p*<0.001), the GF max (*F*(2,62)=13.99; *p*<0.001), and the GF hold (*F*(15.4,59.2)=11.44; *p*<0.001) (see Table 3.1. & Figure 3.3.). Post hoc comparisons showed that the GF at lift-off was significantly greater in the M+L condition as compared to the M condition (mean Δ = 0.41 N; *t*(36)=2.17; *p*=0.04), in the M+H as compared to the M condition (mean Δ = 0.92 N; *t*(36)=3.98; *p*<0.001), and in the M+H as compared to the M+L condition (mean Δ = 0.49 N; *t*(36)=2.40; *p*=0.02). This was also the case for the GF max and the GF hold, which were both significantly greater in the M+L than in the M conditions (GF max: mean Δ = 1.11 N; *t*(36)=3.55; *p*=0.001; GF hold: mean Δ = 0.69 N; *t*(36)=2.45; *p*=0.019), in the M+H than in the M conditions (GF max: mean Δ = 1.92 N; *t*(36)=5.20; *p*<0.001; GF hold: mean Δ =1.32 N; *t*(36)=4.41; *p*<0.001) and in the M+H than in the M+L conditions (GF max: mean Δ = 0.81 N; *t*(36)=2.59; *p*=0.01; GF hold: mean Δ = 0.63 N; *t*(36)=2.4; *p*=0.002). Other ‘condition’, ‘age’ group effects and their interactions were not significant (all *F*<1.4; all *p*>0.15).

There was no effect of ‘time’ (before vs. after), on the measures of the CF (all *F*<0.45; *p*>0.5). Therefore, for each participant, the SM was computed using the average of the CF measures performed before and after the experiment. The SM was significantly different between conditions (*F*(2,62)=21.42; *p*<0.001). The SM was significantly increased in the M+L condition as compared to the M condition (mean Δ = 0.06; *t*(36)=3.39; *p*=0.002), in the M+H as compared to the M condition (mean Δ = 0.11; *t*(36)=5.87; *p*<0.001), and in the M+H as compared to the M+L condition (mean Δ = 0.05; *t*(36)=3.72; *p*=0.001). Other 'condition', 'age' group effects and their interactions were not significant (all *F*<2.6, all *p*>0.08).

Temporal coupling of Grip force and Load force

The cross-correlation analysis between the time course of GF and LF showed a significant main effect of 'condition' on the absolute time lag between GF and LF (*F*(2,62)=3.87; *p*<0.03). The lag was significantly greater in the M condition as compared to the M+H condition (mean Δ = 1.85 ms; *t*(36)=2.67; *p*=0.01), but there was no significant difference between M and M+L conditions (mean Δ = 1.33 ms; *t*(36)=1.79; *p*=0.08) and between M+L and M+H conditions (mean Δ = 0.52 ms; *t*(36)=0.90; *p*=0.37). There was also a main effect of 'age' on the lag (*F*(2,30)=5.95; *p*<0.01). The absolute time-lag was greater in the older group as compared to the young group (mean Δ = 8.35 ms; *t*(14.5)=2.67; *p*=0.02) and the middle aged group (mean Δ = 8.15 ms; *t*(13.7)=2.65; *p*=0.02). For all the parameters of the grip-lift task, the effects of the groups of 'age' never interacted significantly with the factor 'condition' (all *F*<1.4; all *p*>0.2).

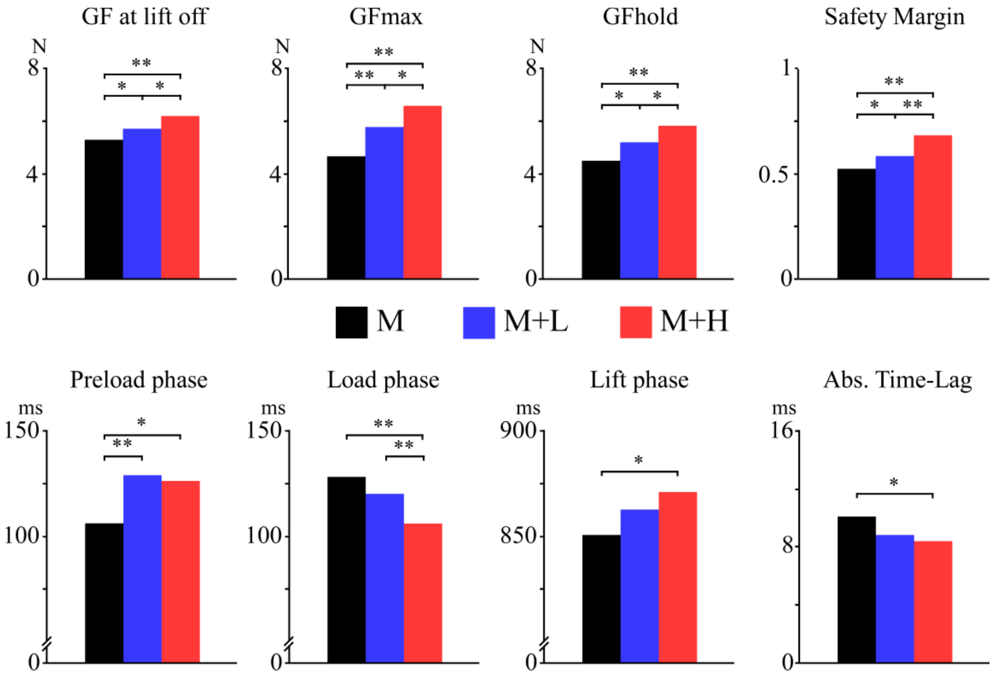

Figure 3.3. Pairwise comparisons of the different measures of motor performance in the M (black bars), M+L (blue bars) and M+H (red bars) conditions. A single asterisk indicates a *p*-value <0.05, double asterisks indicate a *p*-value<0.001.

GF time courses.

The point-by-point ANOVA showed a significant difference in the time courses of GF across the different conditions (Figure 3.4.), extending between 0.98 s to 8.66 s after lift-off (p=0.002). There was no main effect of the factors 'age' and no interaction with these factors. Pairwise comparisons of GF time courses showed that the grip force was significantly increased from 2.25 to 4.45 s in the M+L as compared to the M condition, from 0.98 to 8.64 s in the M+H as compared to M conditions, and from 1.52 to 8.68 s in the M+H as compared to M+L conditions (Figure 3.4.).

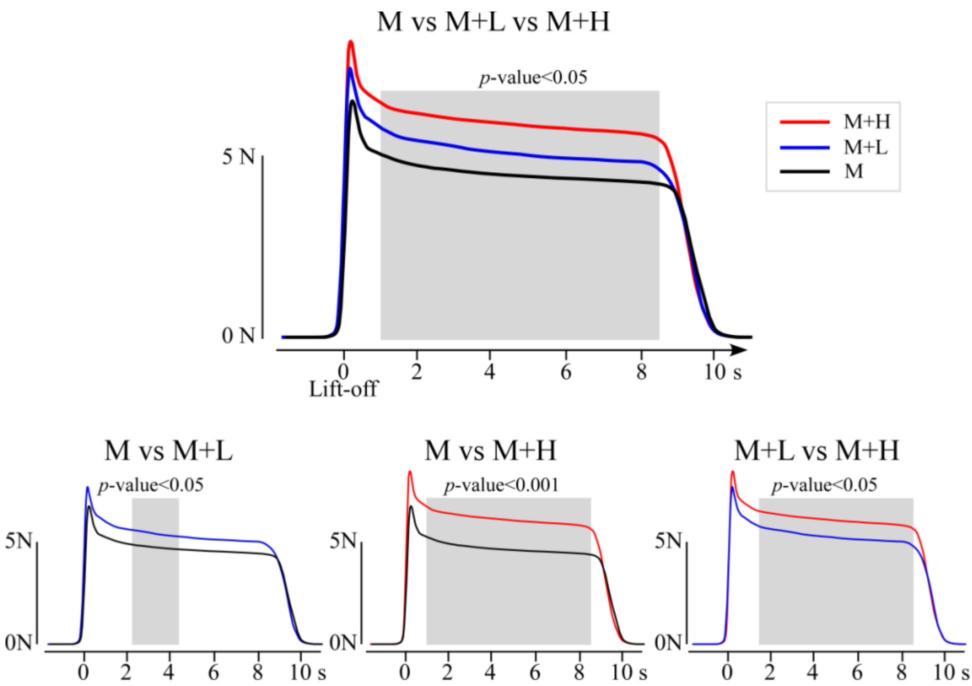

Figure 3.4. Group-level average waveforms of GF obtained in each of the three conditions, after realigning trials to the lift-off of the object. The waveforms were compared using a point-by-point repeated-measures analysis of variance. This analysis revealed a significant difference across the three conditions extending between 0.98 s and 8.66 s after lift-off. There was no main effect of the factor ‘age’ and no interaction with these factors. Post hoc point-by-point t-tests showed that GF was greater in the M+L than in the M conditions from 2.25 to 4.45 s, greater in the M+H than in the M conditions from 0.98 to 8.64 s, and greater in the M+H than in the M+L conditions from 1.52 to 8.68 s.

III.4. Discussion

In the present study, we show that both in young and older healthy adults, performing a cognitive task specifically recruiting working memory interacts with several aspects of the fine grip manipulation of objects, indicating that these aspects of motor control involve high-order cognitive processes. Importantly, as compared to previous studies (Glover et al., 2004; Voelcker-Rehage et al., 2007; Voelcker-Rehage and Alberts, 2007; Li et al., 2009; Hesse and Deubel, 2011; Guillery et al., 2013; Behmer and Fournier, 2014; Kawagoe and Sekiyama, 2014; Quak et al., 2014; Spiegel et al., 2014; Maes et al., 2015; van Dijck et al., 2014; Korotkevich et al., 2015; Bumsuk et al., 2014), performance in present studies during the cognitive task did not involve any motor function and, instead, specifically recruited working memory and related executive functions. For this reason, the interaction between the motor and cognitive tasks observed in the present study cannot be due to competition for resources specifically involved in motor control.

The most striking finding was that, when participants performed a cognitive task, they increased the grip-force applied against the object as soon as they started to lift the object, and this increase was more pronounced in the high-load task (GF at lift-off, GF max, and GF hold) (Figure 3.3. and Figure 3.4.).

Performing a demanding cognitive task can induce autonomic changes leading to a modification of fingertip moistness. Because skin moistness is known to markedly influence the coefficient of friction (André et al., 2010), it was crucial to determine whether the increased grip-force in the dual-task conditions was not merely compensation for a reduction of friction between the fingertip and the manipulated object. For this reason, we measured the coefficient of friction of each participant and found that there was no difference in the coefficients friction measured across trials, conditions and age groups. As the increase in grip force while performing the cognitive tasks was not compensating a reduction of friction, this increase led to an increase in the Safety Margin, i.e. the amount of excessive force applied against the object to prevent it from slipping through the fingers.

Increasing the Safety Margin implies increasing the muscular effort required to perform the motor task, and increasing the risk of damaging the manipulated object if it is delicate. Conversely, increasing the Safety Margin reduces the risk of slippage due to variations in grip force, or to the occurrence of an external perturbation. When participants performed the cognitive tasks, the fluctuations in grip force during the holding phase were not greater than when they performed the motor task alone, indicating that the cognitive task did not affect the constancy of the grip force. Hence, the risk of slippage due to variations in grip force was not increased in the dual task conditions. A possible explanation for the increased Safety Margin in these conditions could thus be that it reduced the need to monitor the environment for possible perturbations that could interfere with the object manipulation and require to adjust the grip force (Westling and Johansson, 1984), or to monitor somatic input from the fingertip that could signal slippage of the object (Johansson and Westling, 1987), such as the afferent input that might be generated during partial slip (Johansson and Westling, 1987).

In addition to increasing their grip force, participants also increased the duration of the Preload phase. This increase was similar in the low- and high-load cognitive tasks, and was also observed in our previous study (Guillery et al., 2013). The Preload phase is thought to constitute a time interval during which participants collect somatosensory information from the fingertips to plan the appropriate motor command (Johansson and Westling, 1984). This effect of the cognitive task indicates that the Preload phase involves processes that are not purely automatic and, instead, require higher-order cognitive resources. In contrast, the duration of the Load phase was significantly reduced when participants performed the high-load cognitive task, but not when they performed the low-load cognitive task. The correlation between the time courses of grip and load forces was similar across the conditions, but the time lag between the grip force and the load force was reduced when participants performed the cognitive tasks. Previous studies performed in children have shown that the coupling between grip and lift forces during object manipulation involves processes that mature and become more automatic with age (Forssberg and Eliasson, 1991; Cole and Beck, 1994). When performing a demanding cognitive task, adult participants may further rely on these automatic processes to reduce the need for higher-order cognitive resources, leading to a reduction of the time-lag between grip and load forces, and a reduction of the total duration of the Load phase.

To conclude, mimicking the everyday activity of fine-grip object manipulation, our experiment confirms that the performance of the apparently simple and automatic motor activity of grasping and lifting an object is under the influence of higher-order cognitive processes. Several previous studies have advocated the clinical usefulness of assessing the performance of a grip-lift task to evaluate motor function in patients (Johansson and Flanagan, 2009; Berner et al., 2007). However, these clinical assessments are always performed in isolation. Assessment of the dynamic and temporal parameters of the grip-lift task in a dual-task paradigm could provide a better-suited tool to assess motor performance during cognitive load, i.e. in conditions closer to real life situations. Following a lesion of the nervous system affecting the transmission or processing of sensory input and motor output, future studies should examine whether the performance of the grip-lift task becomes even more dependent on the availability of cognitive resources. Most importantly, assessing motor performance under cognitive load might be a more sensitive mean to actually assess motor abilities and its impact in real life situations.

CHAPTER IV. Cognitive-Motor Interference In Chronic Stroke Participants: a Pilot Study.

In Preparation: Guillery, E., Mouraux, A., Legrain V., Halkin V., and Thonnard, J.-L. Cognitive-motor interference in chronic stroke participants: a Pilot Study.

IV.1. Introduction

In our daily life, object manipulation is most often performed concomitantly to other tasks involving higher-order cognitive functions, such as manipulating a glass while having a conversation, or interacting with a computer or a smartphone. Yet, recent studies have shown that performing a higher-order cognitive task may interfere with the realization of upper limb movements. They used dual-task paradigms involving a motor task simultaneously performed with a concurrent cognitive task. Motor tasks range from a simple object manipulation, like reaching and grasping task (Li et al., 2009; Spiegel et al., 2013, 2014; Gunduz Can et al., 2017), precision grip-lift task (Guillery, Mouraux and Thonnard, 2013; Bumsuk *et al.*, 2014; Guillery *et al.*, 2017), precision and power grip squeezing task (van Dijck et al., 2014); force tracking task (Voelcker-Rehage et al., 2007; Mehta and Agnew, 2011; Au and Keir, 2007; Temprado et al., 2015); reach and grasp familiar hand tools (Creem and Proffitt, 2001), tapping task (Serrien, 2009; Fraser et al., 2010; Korotkevich et al., 2015); to the complex cellists' bowing movements (Maes et al., 2015). Several different cognitive processes were used as Cognitive task: semantic memory: with action-related, or not, words (Creem and Proffitt, 2001; Glover and Dixon, 2002; Glover et al., 2004); associative memory (Li et al., 2009; Singhal et al., 2007); working memory (WM): with Stroop task (Au and Keir, 2007; Mehta and Agnew, 2011), N-back tasks (Voelcker-Rehage et al., 2007; Gunduz Can et al., 2017), counting task (Serrien, 2009; Fraser et al., 2010; Korotkevich et al., 2015), letters rehearsal tasks (Guillery *et al.*, 2017); or even complex visual searching and counting task (Guillery et al., 2013). In these studies, the concurrent cognitive tasks interfere with the motor tasks. Moreover, the motor planning, the execution and the online control of the task, recruit the capacity-limited cognitive resources which are also required for performing the cognitive task (Guillery, Mouraux and Thonnard, 2013; Spiegel, Koester and Schack, 2013; Guillery *et al.*, 2017). Motor tasks interfered with WM and the decrease in motor performances was larger for the visuospatial task as compared to the verbal task (Weigelt et al. 2009).

The underlying mechanisms of the dual-task interaction are still debated in the literature. According to the limited attentional resources model, when participants perform a highly demanding cognitive task, the attentional load will reduce the available resources needed to process task-irrelevant stimuli (Legrain et al., 2009).

In previous studies (Chapter II (Guillery, Mouraux and Thonnard, 2013) and III (Guillery *et al.*, 2017)), we use the concept of cognitive-motor interference to evaluate the involvement of high-level cognitive processes on dexterous manipulation by combining a motor grip-lift task to a working memory task. We found that dexterous manipulation, a highly habitual and seemingly automatic behaviour, involves high-order functions, in healthy participants. The function of grasping and lifting an object is extensively described in the literature (Johansson and Westling, 1984; Westling and Johansson, 1984; Johansson *et al.*, 2010). It is a well-established model to study sensorimotor and cognitive control processes of the human sensorimotor system (Flanagan, Bowman and Johansson, 2006; Nowak, Glasauer and Hermsdörfer, 2013). Several studies advocated the clinical usefulness of assessing the performance of the grip-lift task to evaluate motor function in chronic stroke participants (Nowak et al., 2004; Nowak and Hermsdörfer, 2006; Johansson and Flanagan, 2009; Berner et al., 2007). However, these clinical assessments are always performed in isolation. Participants had to focus only on the one assigned task, a situation far from everyday reality.

In the present experiments, we recruited chronic post-stroke participants suffering from a moderate impairment of manual dexterity. Our aim was to examine whether conducting a dual motor-cognitive task would lead to a stronger motor-cognitive interaction as compared to healthy age-matched controls.

Stroke is one of the first worldwide leading causes of long-term disability (Mensah, Norrving and Feigin, 2015). Only approximately 12% of stroke survivors achieve complete motor recovery after 6 months (Kwakkel et al. 2003). Some studies are reporting over 90 per cent of stroke survivors suffering from upper limb motor disability (Parker, Wade and Hewer, 1986; Broeks *et al.*, 1999).

Manual dexterity is frequently impaired in this population, resulting in long-term functional deficits (Bleyenheuft and Gordon, 2014). Patients with cortical, subcortical and cerebellar stroke exhibit alteration of forces scaling and deficits in the temporal coupling of the grip and load forces (Hermsdörfer *et al.*, 2003; Nowak, Hermsdörfer and Topka, 2003; Nowak, 2006; Anens, Kristensen and Häger-Ross, 2010). Both predictive and reactive controls of the movement are perturbed (Dispa et al., 2014; Bleyenheuft and Gordon, 2014).

These alterations suggest that the internal models responsible for the precise regulation of forces are impaired. Actually, the predictive mechanism is present but altered in the paretic hand (Takahashi and Reinkensmeyer, 2003; Raghavan, Krakauer and Gordon, 2006). In the grip-lift task, due to both sensory and motor deficits, the timing and scaling of grip force, and coupling between grip and lift forces, are also significantly altered, even in the presupposed unaffected hand, ipsilateral to the lesion, in patients with subcortical middle cerebral artery stroke (Quaney *et al.*, 2005; Nowak *et al.*, 2007). In other words, in chronic stroke participants, the neural processes of predictive and reactive mechanisms involved in the planning and the execution of the movements are perturbed.

Since chronic stroke participants have sensorimotor deficits, one can hypothesize that they must rely more on their high-level cognitive functions to monitor their behaviour. Hence, performance in the motor task could be more affected by the concurrent performance of a cognitive task in dual-task conditions, with greater alterations of performances when performing the more demanding cognitive task. This expected cognitive-motor interaction could lead to an increase of Grip Forces (GF) a reduction of the coupling between GF and Load Force (LF), and a lengthening of temporal parameters. We also expected greater alterations of performances in their affected hand as compared to the contralateral hand.

IV.2. Methods

Participants

Eleven chronic stroke participants took part in the experiment (8 men and 3 women, mean age: 62 ± 16, range: 40-84). The time since stroke, Lesion type and its localization are reported in table 4.1. All participants had normal or corrected to normal vision. The remaining ability to grip, lift and hold an object during several seconds repetitively was an inclusion criterion. Participants did not receive financial compensation for their participation and they all provided written informed consent. The study was approved by the local ethics committee.

Participant	Sex	Age (years)	Stroke onset (month)	Lesion Type	Localization	Laterality	Affected Hand
1	W	49	13	I	C	R	L (ND)
2	M	81	5	H	S	R	R (D)
3	W	40	9	I	S	L	R (ND)
4	M	76	93	I	S	R	R (D)
5	M	56	19	I	C	R	L (ND)
6	M	55	11	I	S	R	L (ND)
7	M	75	13	I and H	C	R	L (ND)
8	M	71	269	I	S	R	R (D)
9	M	42	15	I	S	R	L (ND)
10	W	84	6	I	S	R	R (D)
11	M	48	12	H	C and S	R	L (ND)

Table 4.1. Clinical description of chronic stroke participants. W = woman, M = man; I = ischemic, H = haemorrhagic; C = cortical, S = subcortical; R = right-handed, L = left-handed; D = dominant, ND = non-dominant.

Pre-experimental assessment

Before the actual experiment, the motor and cognitive abilities of the participants were assessed with the following tests.

Motor assessment

Handedness was tested with the Edinburgh Oldfield Handedness Inventory (Oldfield, 1971). Upper limb activity limitations were assessed with the Abilhand questionnaire, validated and calibrated for chronic stroke participants (Penta et al., 2001) (Appendix B: Figure B.1. & B.2.). Dexterity was assessed by the Purdue Pegboard test for digital dexterity (Tiffin and Asher, 1948) and the Box and Block test for manual dexterity (Mathiowetz et al., 1985). Only the 5 last chronic stroke participants performed the Box and Block test. Their maximum voluntary contraction of Pinch grip (MVC Pinch grip) was assessed with the same instrumented object used in the previous experiment (Guillery et al., 2013;

Guillery et al., 2017) (Chapter II and III). Participants were asked to grip the apparatus with the tips of their index and the thumb, with the maximum force they can develop, in the same position as in the experiment, i.e. in a sitting position, elbow at 90°, in a neutral position of pro-supination of the wrist. The average of three trials for each hand was used as their MVC scores. Between each trial of the same hand, 30 s of rest was respected. Participant scores were compared to the norms from scientific literature to obtain Z-scores, for the Purdue Pegboard test (Tiffin & Asher 1948; Desrosiers et al. 1995), the Box and Block test (Mathiowetz, Volland, et al. 1985; Desrosiers et al. 1994) and the Pinch grip (Mathiowetz, Kashman, et al. 1985). Values of Z-score among ± 2 are considered as normal, values above +2 or below -2 are abnormal.

Cognition assessment

Cognitive abilities were evaluated with the Mini-Mental State Examination (MMSE) (Folstein et al., 1975) (Appendix A: Figure A.1 & A.2.). Most importantly, the pre-experimental evaluation included an assessment of memory span for letters, i.e. the capacity of working memory to rehearse a serie of letters for their immediate use (Conway et al., 2005). This was achieved in order to individually adjust the working memory task of the experimental session to the abilities of the participant and, thereby, avoid using a series of items beyond working memory capacity. The assessment of working memory span was similar to the standard Digit Span subtest of the Wechsler Memory Scale (Wechsler, 1981). Participants were asked to memorise a series of consonant letters presented on a screen during 2.25s and to repeat the entire series in the correct order immediately after they disappeared from the screen. Vowels were not used in order to prevent participants from chunking the letters into pronounceable words or pseudo-words. Meaningful sequences such as acronyms were also avoided. Trials started with a series of three letters. After each repetition of two successful trials, one item was added to the series. Otherwise, the procedure was stopped. The length of the longest series a participant could repeat successfully was considered as his memory span of letters.

Stimuli and Procedure

The apparatus used to perform the grip-lift task, the visual and auditory stimuli, the procedures and the measures were exactly the same as those used in Chapter

II (Figures 3.1.& 3.2.). The only difference consisted in the evaluation of the two hands of the participants, one by one. Participants sat comfortably in a chair in front of a desk supporting the apparatus and the monitor. During the experiment, they were instructed to keep their non-active hand at rest, and their active hand around the apparatus. Participants were asked to perform the different tasks under three conditions and with one of their hands, one condition and one hand at a time. In the first condition (M), participants performed a motor task without any concomitant cognitive task. In the second and third conditions, participants concomitantly performed the same motor task with either the low-load cognitive task (M+L) or the high-load cognitive task (M+H). The cognitive tasks consisted to remember an adapted list of letters in alphabetical or in random order. At the end of each trial a letter reappeared, participants had to tell which was the following letter in the initial list. Thus, in a first easy dual-task condition, concomitantly with the motor task, participants had to recruit semantic memory only at the end of each trial, and, in the second more difficult dual-task condition, they had to remember systematically the list of letters during the whole trial, relying on their working memory. They were asked to perform the cognitive tasks as fast and as accurately as possible. In the dual-task conditions, they were not asked to give priority to the motor or to the cognitive tasks. Participants were given the opportunity to practice the tasks before the experiment in five consecutive trials for each condition and each hand. Next, participants performed 12 experimental blocks of 8 trials each, two blocks per condition and per hands. The order of the conditions was counterbalanced across participants. Instructions about the task were given verbally at each onset of a new block of trials and also on request. In the M+L and M+H conditions, each trial started with the presentation of a memory set consisting of a list of letters on the screen. The letters were chosen among the same following list of letters: J, K, L, M, N, P, Q, R, S, T, V. The length of the set was adapted individually to match the length of the memory span for letters assessed before the beginning of the experiment as in our previous study (Guillery *et al.*, 2017). The length of the set was fixed for each participant for the whole experiment. During recorded trials, we asked participants not to speak until they lift off the object on the table in Motor only condition, or until they gave their answer to the cognitive task in dual-task conditions. Participants were instructed to perform the task(s) of the different conditions as fast and accurately as possible, and no prioritisation instruction over a task on the other was given.

Measures

The performance of the cognitive tasks was assessed by computing the percentage of correct answers, i.e. the percentage of trials for which the correct letter of the memory set was reported, in each dual-task conditions. Forces (in Newton) were analysed using Matlab 7.5 (The MathWorks, Inc., MA). Signals were low-pass filtered using a Butterworth filter (cutoff: 15 Hz; slope: 2dB). Typical GF and LF traces are shown in Figure 3.2 (Guillery et al., 2013).

The time course of the grip-lift movement can be decomposed into series of distinct phases: the Preload phase, the Load phase, the Lift phase and the Hold phase (Johansson and Flanagan, 2009a; Guillery, Mouraux and Thonnard, 2013) (Figure 1.3). The Preload phase is defined as the time between initial contact of the fingers with the apparatus and the onset of the load force (LF > 0.1 N), i.e. when participants start to apply an upward vertical force to load the object. The Load phase is defined as the time during which both GF and LF increase up to the instant when LF equals the weight of the apparatus (2.75 N), i.e. the instant when the apparatus is actually lifted from the table. The Lift phase is defined as the time interval during which the apparatus is lifted upwards until stabilisation above the table. Finally, the Hold phase is defined as the time interval during which the apparatus remains stable above the table.

In addition to assessing the duration of these phases, the GF and LF forces measured at different time points were used to summarise the performance of the motor task: GF at lift off, GF max and GF hold. The GF at lift off provides information about the grip force applied at the very early stage of the movement. The GF max corresponds to the maximum grip force applied during the trial and usually occurs at the end of the Lift phase. The GF hold is computed by averaging the GF during the Hold phase, it provides information about how the GF is maintained while the apparatus remains stable above the table. The GF hold is also used to compute the Safety Margin (SM). The SM provides information on the excess of grip force applied onto the object to prevent it from slipping through the fingers. It is expressed as the ratio between the excess of grip force while holding the object: (GF hold – GF at slip) divided by the GF hold.

Coefficient of friction

The amount of grip force required to lift the object without letting it slip through the fingers is dependent on the coefficient of friction between the fingers and the object surface. Therefore, before and after the experiment, we estimated the skin-apparatus coefficient of static friction (CF) of each hand by asking participants to perform a series of 8 lift-and-drop manoeuvres with the apparatus. The participants lifted and held the instrument stationary, then gradually released the grip until the object slipped due to gravity (Johansson and Westling, 1984). For each lift-and-drop manoeuvres, the static coefficient of friction (CF) was estimated as half the LF/GF ratio at slip onset (Johansson and Westling, 1984).

Statistical analyses

Statistical analyses were performed using SPSS 23 (IBM, NY). For all analyses, the significance level was set at $p < 0.05$. The memory span of letters of chronic stroke participants was compared with that of age-matched healthy participants of our previous study (Guillery *et al.*, 2017) (Chapter III) using an analysis of variance (ANOVA). The impact of the cognitive tasks on the performance of the motor task (M vs. M+L vs. M+H) of the two hands (less affected vs. affected) was assessed by comparing the different temporal and force measures obtained from the grip-lift task using an ANOVA with 'condition' (M vs M+L vs M+H) and with 'hand' (less affected vs affected) as within-subject factors. Values of CF obtained before and after the experiment were compared using the same ANOVA. Greenhouse-Geisser and Huynh-Feldt corrections for degrees of freedom, and contrasts analyses with Student paired *t*-tests, were used when necessary. Effect sizes were estimated by means of partial eta squared and sensitivities were estimated by observed power.

Finally, to compare the time courses of GF during the grip-lift task performed in the different conditions and with the two hands, single-subject average waveforms of GF obtained for each of the three conditions, aligned relative to lift off, were compared using a point-by-point ANOVA with 'condition' and 'hand' as within-subject factor. This method allowed identifying the time intervals where the GF traces showed a significant main effect of 'condition', 'hand', or a significant interaction between the five factors. When significant, the same method was applied to compare the different average waveforms of GF of each condition pairwise, using point-by-point t-tests.

IV.3. Results

Participants

According to the Edinburgh Oldfield Handedness Inventory (Oldfield, 1971), at the days of the experiment 10 participants were right-handed and 1 was left-handed. Their score at the MMSE was 29.1 ± 1.8 (mean ± standard deviation). This indicates the absence of any blatant cognitive deficit. One participant had a score of 24/30 which is the floor score before considering it abnormal (Crum et al., 1993). The mean span of letters was 6 letters ± 1 and range from 4 to 7 letters. This span is significantly lower than the span of healthy participants from our previous experiment ($t(46)=3.12$, $p=0.003$).

For the ABILHAND, chronic stroke participants got an average score of 2.1 logits ± 1.2, (range from 0.3 to 4.3 logits), which means that they got very mild or mild difficulties in their manual abilities. Only the most difficult items, as "Hammering a nail" which requires the highest manual ability, were perceived the more difficult, but still not impossible. When asked none of them reported having paresis or spasticity that could affect upper limb movement and dexterous manipulation. Their average scores on the Purdue Pegboard test were 12 sticks ± 3 for their less affected hands (range from 5 to 17 sticks) and 6 sticks ± 4 for their affected hands (range from 0 to 13 sticks). Average scores of the 6 last participants in the Box and Block test were 62 blocks ± 11 for their less affected hands (range from 50 to 80 blocks) and 49 blocks ± 30 for their affected hands (range from 6 to 82 blocks). Average scores of participants Maximal Voluntary Contraction (MVC) were 45.6 N ± 14.5 for their less affected hands (range from 23 to 66 N) and 37.4 N ± 14.6 for their affected hands (range from 14 to 51 N). On average and overall, when compared to the norms, scores from the less-affected hand has diminished values in the different tests, with 3 participants significantly below the norms in Purdue Pegboard test and 9 in the MVC Pinch Grip test, but not on the Box and Block test. On average the affected hand was significantly below the mean in the different tests, with only 2 participants among the norms in Purdue Pegboard test and 2 over 5 in the Box and Block test, and also 2 in the MVC Pinch Grip test. Detailed results are reported in Table 4.2.

Participant	Abilhand (logit)	MMSE	letterSpan (Nb)	Purdue Pegboard (Z-score)		Box and Block (Z-score)		MVC Pinch Grip (Z-score)	
				Less Affected	Affected	Less Affected	Affected	Less Affected	Affected
1	2.7	30	5	-0.4	-6.7	ø	ø	-2.3	-1.8
2	1.4	29	5	0.7	-2.6	ø	ø	-1.4	-2.5
3	0.3	30	7	-3.9	-9.7	ø	ø	-3.7	-3.5
4	0.7	30	5	-2.7	-4.7	ø	ø	-4.3	-3.0
5	3.3	30	6	-1.0	-4.8	ø	ø	-3.3	-3.1
6	1.7	29	6	-2.3	-8.4	ø	ø	-3.4	-4.2
7	2.0	28	5	-1.0	-4.9	-1.8	-6.6	-3.0	-4.6
8	1.6	30	5	-0.2	-1.3	-0.7	-2.3	-2.0	-5.0
9	3.1	30	6	-1.4	-2.8	-0.4	0.2	-4.2	-3.1
10	4.3	24	4	0.8	0.8	0.2	1.1	0.0	-1.1
11	1.7	30	6	-1.7	-5.2	-1.8	-5.0	-4.0	-2.6

Table 4.2. Motor and Cognitive pre-experimental assessments of chronic stroke participants. Participants' Z-scores were obtained by comparing actual scores to the norms from the scientific literature. Values of Z-score among ± 2 are considered as normal, values above +2 or below -2 are abnormal.

Performance of the cognitive task

The participants provided the correct answer to the cognitive task in 98 ± 3 % of trials in the M+L condition with their less affected hand, and 98 ± 4 % of trials with their affected hand. In the M+H condition, participants provided the correct answer in 71 ± 20 % of trials in the M+L condition with their less affected hand, and 65 ± 22 % of trials with their affected hand. There is a strong difference between the two conditions ($F(1,10)=23.34$, $p<0.001$), and no difference between the 2 hands ($F(1,10)=1.92$, $p=0.2$). As expected, participants made more mistakes in M+H condition.

Performance of the motor task

The percentage of failed trial in grip-lift-task leading to an error of motor task was under 1%. By *failing* in the motor task, we mean a slip, a too long delay before lifting or replacing the apparatus or no lift at all. Thus the cognitive tasks did not strictly interrupt the ongoing of the grip-lift task.

Table 4.3. presents the main effects of repeated measures ANOVA with the factors ‘condition’ and ‘hand’ and their interaction effect. Effect sizes were estimated by means of partial eta squared values and sensitivity were estimated by observed power. Table 4.4. presents the post hoc pairwise comparisons of the parameters of interest showing factors effects of both ‘condition’ and ‘hand’ factors or an interaction effect. The pairwise comparisons across the three conditions and two hand factors led to fifteen comparisons. Figure 4.1. illustrates the comparisons between typical traces of Grip Force and Load Force of the less-affected and the affected hand of participants, and also the typical trace of the dominant hand of healthy participants, in the three traces from the three conditions of the dual-task paradigm. Figure 4.2. illustrates the comparisons of eight parameters of the grip-lift task between the three conditions, the less affected hand and the affected hand of chronic stroke participants, and the dominant hand of healthy participants.

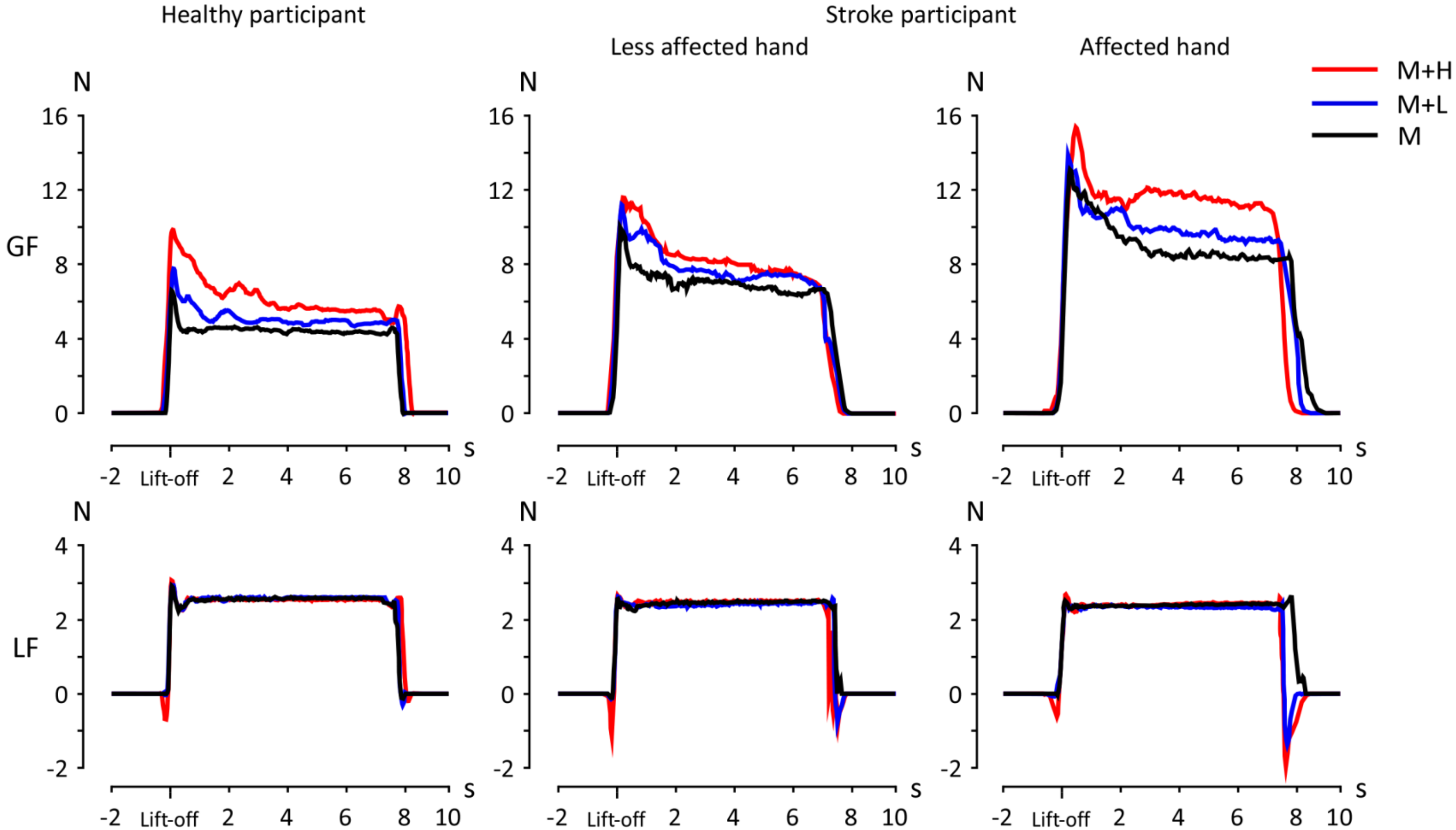

Figure 4.1. Comparison of typical traces of Grip Force (GF) and Load Force (LF) of healthy participants (Chapter III), Less-affected and Affected hands of chronic stroke participants, in the Motor only condition (M; black), the Motor + Low load cognitive condition (M+L; blue) and the Motor + High load cognitive condition (M+H; red) Values are in Newton.

Time parameters

Preload phase

There were significant main effects of 'condition' factor ($F(2,20)=25.5$, $p<0.0001$) and 'hand' factor ($F(1,10)=7.4$, $p=0.02$) on the duration of the preload phase, but there was no interaction between the two factors ($F(2,20)=0.2$, $p=0.80$). The duration of the preload phase significantly increased when performed with the affected hand as compared to the less affected hand. The duration of the preload phase was significantly lengthened between the M and the M+L condition (mean Δ = 20ms; $t(10)=3.2$, $p=0.01$), between the M and the M+H conditions (mean Δ = 46ms; $t(10)=6.0$, $p<0.0001$) and between the M+L and the M+H conditions (mean Δ = 26ms; $t(10)=4.6$, $p=0.001$). Even though there was no interaction effect, we compared the performances in the two hands separately, as exploratory statistics, as presented in Table 4.4. When participants were using their less affected hand, the durations of the preload phase of the grip-lift task were significantly greater with the increasing difficulty of the conditions (all mean Δ > 23ms; all $t>2.4$ and all $p<0.04$). When participants were using their affected hand, the durations of the preload phase of the grip-lift task were about the same between the M and the M+L conditions (mean Δ = 13ms; $t(10)=1.3$, $p=0.22$), the difference between the M+L and the M+H conditions (mean Δ = 29ms; $t(10)=2.2$, $p=0.06$) was not significant, however, the duration of the preload phase was significantly greater in the M+H conditions than in M condition (mean Δ = 42ms; $t(10)=3.1$, $p=0.01$). Overall, the durations of the preload phase of the grip-lift task increased with the difficulty of the conditions and with the affected hand.

Load phase

The repeated measures ANOVA revealed no main effects of 'condition' factor ($F(2,20)=0.4$, $p=0.67$) and no interaction on the duration of the load phase ($F(2,20)=1.7$, $p=0.20$), but there was a main effect of 'hand' factor ($F(1,10)=21.2$, $p<0.001$). The duration of the load phase performed with the less affected hand was significantly greater than the duration of the load phase performed with the affected hand (mean Δ = 91ms).

Lift phase

There were no main effects of 'condition' and 'hand' factors, and no interaction on the duration of the lift phase (all $F<3.1$, all . $p>0.11$). In this experiment, the lift phase was not affected by the cognitive tasks or the affected hand.

Temporal coupling of Grip force and Load force

Considering the coefficients of cross-correlation, there was no main effect of 'condition' factor ($F(2,20)=0.18$, $p=0.07$), while there was a main effect of 'hand' factor ($F(1,10)=16.0$, $p=0.003$). The coefficients of cross-correlation were significantly greater when performed with the less affected hand than when performed with the affected hand (mean Δ =0.11). The interaction between the two factors was significant ($F(2,20)=2.5$, $p=0.02$). However, the post hoc did not bring more information than those revealed by the main effects of factors (Table 4.4).

There was a significant main effect of 'condition' ($F(1.1,11.4)=8.6$, $p=0.01$) and a significant interaction between 'condition' and 'hand' ($F(1.1,11.4)=4.6$, $p=0.05$) on the duration of the absolute time lag, but no significant main effect of 'hand' ($F(1,10)=4.6.0$, $p=0.06$). The different durations of the absolute time lag in each hand were compared separately (Table 4.4). The duration of the absolute time lag in the M+H condition with the affected hand was significantly longer than the absolute time lag in all other conditions and with both hands (all $t<2.2$, all $p<0.05$). When performed with the affected hand, the M+H condition was 18ms longer than in the M condition ($t(10)=2.7$, $p=0.02$) and was 8ms longer than in the M+L condition ($t(10)=3.5$, $p=0.006$). When compared to the conditions performed with the less affected hand, the M+L condition performed with the affected hand was 50ms longer than in the M condition ($t(10)=2.3$, $p=0.04$), it was also 50ms longer than in the M+L condition ($t(10)=2.4$, $p=0.04$) and 48ms longer than the M+H condition ($t(10)=2.2$, $p=0.05$) The other differences between the duration of absolute time lag between the other combinations of 'condition' and 'hand' factors were no significant (all $t<2.1$ and $p>0.06$). The absolute time lag was lengthened with the increasing difficulty of the dual-task, with a more blatant impact on the affected hand.

Force parameters

GF at lift off

There were no main effects of ‘condition’ and ‘hand’ factors, and no interaction on the GF at lift off values (all $F<3.4$, all . $p>0.10$). In this experiment, the GF at lift off was not affected by the added cognitive tasks and was not different between hands.

GFmax

There were significant main effects of ‘condition’ ($F(2,20)=7.1$, $p=0.01$) and ‘hand’ factors ($F(1,10)=6.6$, $p=0.03$) on the GFmax values, but no interaction between the two factors ($F(2,20)=1.3$, $p=0.31$). The values of GFmax in the M+H condition were significantly higher than in the M condition (mean Δ = 1.5N; $t(10)=3.7$, $p=0.004$). The difference between the M and the M+L conditions (mean Δ = 0.9N), and, the M+L and the M+H conditions (mean Δ = 0.6N) were not significant (all $t<2$, all $p>0.07$). Overall the GFmax obtained from the affected hand were higher than those obtained through the less affected hand (mean Δ = 3.19N). Going further (Table 4.4), it was revealed that the differences between conditions performed with the less affected hand only were not significant (all $t<1.2$ and $p>0.24$). Considering the affected hand only, there was significant difference between the M and the M+H conditions (mean Δ = 2.2N; $t(10)=4.2$, $p=0.002$), and there were no significant differences between the M and the M+L conditions (mean Δ = 0.9N; $t(10)=1.6$, $p=0.13$) and between the M+L and the M+H conditions (mean Δ = 1.4N; $t(10)=2.0$, $p=0.07$). GFmax was significantly increased in the M condition performed with the affected hand as compared to the M+L condition performed with the less affected hand (mean Δ = 1.7N; $t(10)=3.1$, $p=0.011$). GFmax was significantly increased in the M+L condition performed with the affected hand as compared to the M condition (mean Δ = 3.5N; $t(10)=3.1$, $p=0.01$) and the M+L condition (mean Δ = 2.6 N; $t(10)=5$, $p=0.001$) performed with the less affected hand. GFmax was also significantly increased in the M+H condition performed with the affected hand as compared to the M condition (mean Δ = 4.8N; $t(10)=3.4$, $p=0.007$), the M+L condition (mean Δ = 4N; $t(10)=7.3$, $p<0.001$), and the M+H condition (mean Δ = 4.2N; $t(10)=2.5$, $p=0.03$) performed with the less affected hand. The last comparisons were not significant (all $F<2.15$ and $p>0.06$). Thus, seven comparisons involving the affected hand were significant (over twelve). The GFmax were significantly greater with the affected hand than with the less affected hand. GFmax also increased with the difficulties of the dual-task performed with the affected hand but not with the less affected hand.

GFhold

There were significant main effects of ‘condition’ ($F(2,20)=33.1$, $p<0.001$) and ‘hand’ factors ($F(1,10)=10.5$, $p=0.009$), and no interaction ($F(1.1,11.4)=1.1$, $p=0.33$) on the values of GFhold. The values of GFhold were significantly increased in the M condition to the M+H condition (mean Δ =0.76N; $t(10)=3.9$, $p=0.003$), in the M+L condition to the M+H condition (mean Δ =0. 83N; $t(10)=4.6$, $p=0.001$) and in the M condition to the M+H condition (mean Δ =1.59N; $t(10)=7.7$, $p<0.001$). Values of GFhold obtained through the affected hand were significantly greater than those obtained through the less affected hand (mean Δ =1.59N). When going further (Table 4.4) it was revealed that almost all comparison between each condition in each hand (ten over fifteen) were significantly different (all $t>2.36$, all $p<0.04$) excepting the differences between the M+L condition with the less affected hand and the M and M+H conditions in the same hand (all $F<1.01$ and $p>0.34$), and, between the M condition of the affected hand and the M+L condition with the less affected hand, and also the M+L and M+H condition with the less affected hand (all $F<2.02$ and $p>0.07$). The GFhold was almost always significantly greater with the affected hand than the less affected hand, and the GFhold increased with the difficulty of the dual-tasks with both hand.

Coefficient of friction and safety margin

There was no effect of ‘time’ (before vs. after) ($F(1,9)=.001$; $p=0.98$), but there was an effect of ‘hand’ (Less affected vs Affected) ($F(1,9)=7.9$; $p=0.02$) on the measures of the CF. There were no interaction effect ($F(1,9)=1.83$; $p=0.21$). Therefore, for each participant, the SM was computed using the average of the CF measures performed before and after the experiment in their less affected and affected hand separately. There was a significant main effect of ‘condition’ factor on the values of the safety margin ($F(1.2,12.0)=5.0$, $p=0.04$). Since there is no effect of ‘hand’ factor ($F(1,10)=3.4$, $p=0.10$) and no interaction effect ($F(1.1,11.3)=0.43$, $p=0.07$), the main effect of ‘condition’ could be explained by the significant differences between the M condition and the M+H condition (mean Δ =

0.04; $t(10)=2.52$, $p=0.03$). As showed by the Eta squared, the effect was pretty large (0.46), and the observed power was acceptable (0.80), however, the statistically significant difference should be considered with caution according to the marginal value of the difference. Moreover, the differences between the M and the M+L conditions (mean $\Delta = 0.01$), and between the M+L and the M+H conditions (mean $\Delta = 0.03$) were not significant (all $t<1.94$ and $p>0.08$).

All these data are illustrated in Figure 4.2.

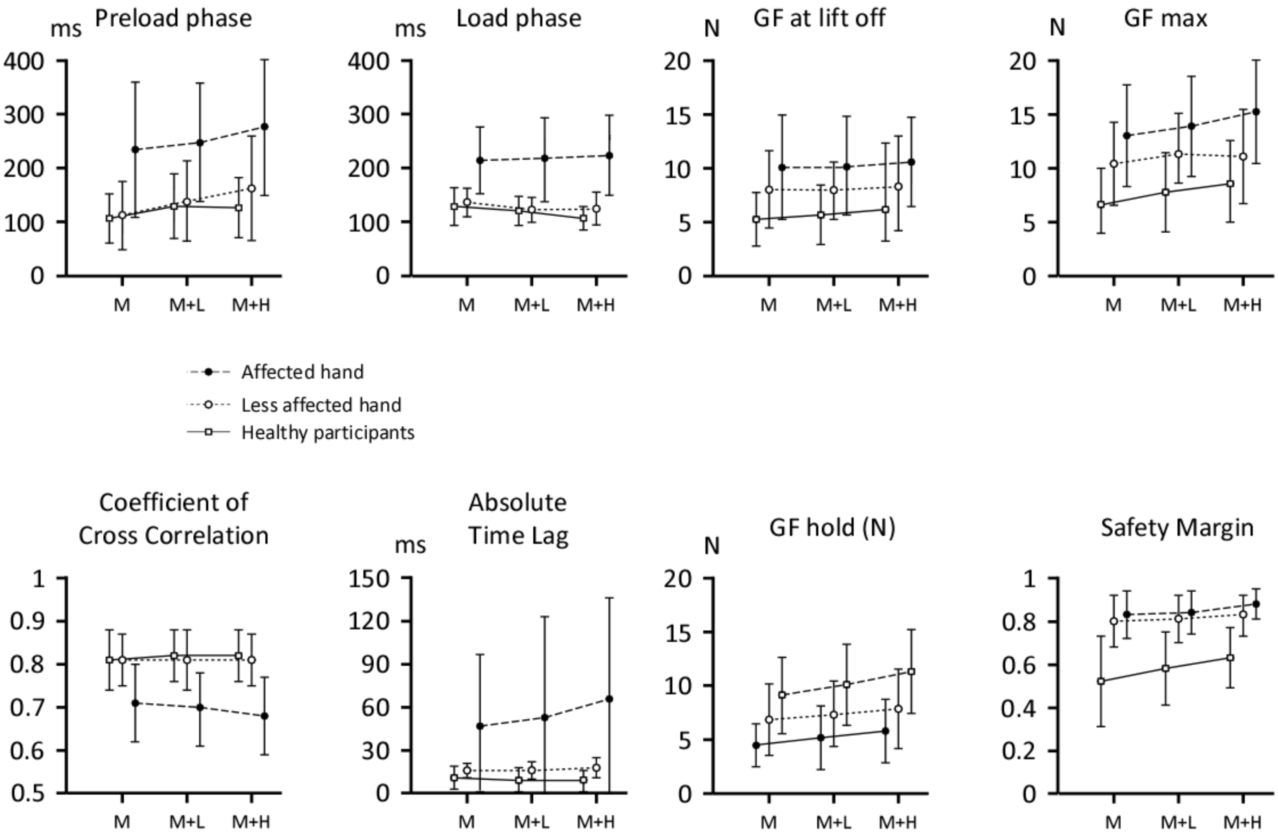

Figure 4.2. Comparisons of the different measures of motor performance in the M, M+L and M+H conditions performed by the healthy participants (Chapter III) (empty square, continuous line), the Less-affected hand of Chronic stroke participants (empty dot, short discontinuous line) and the Affected hand of chronic stroke participants (full black dot, long discontinuous line). Values are in Newton (N) and millisecond (ms).

GF time courses

The group-level average waveforms of GF obtained in each of the three conditions, after realigning trials to the lift-off of the object, for the less-affected and affected hands, is illustrated in Figure 4.3. The point-by-point ANOVA showed a significant difference in the time courses of GF across all the different conditions, extending between 0.57 s to 5.66 s after lift-off.

The same analysis was conducted to compare the fifteen pairwise comparisons between the time courses of GF of each trace from each condition and hand. Preliminary results showed a significant difference in the time courses of GF extending for about the same length for every single group comparison (excepted when comparing the M+H of the affected hand and the M conditions of the less affected hand, the M+L and the M+H conditions of the affected hand, the M and the M+L conditions of the less affected hand, and the M and the M+H conditions of the less affected hand, which have no significant difference).

Time Parameters	Main effect of :	Rm ANOVA *F*	df	*p*-value	η²	Observed Power
Preload phase	condition	25.5	2,20	**<0.001**	0.71	1.00
	hand	7.4	1,10	**0.02**	0.42	0.69
	Interaction	0.2	2,20	0.80	0.02	0.08
Load phase	condition	0.4	2,20	0.67	0.04	0.11
	hand	21.2	1,10	**<0.001**	0.68	0.99
	Interaction	1.7	2,20	0.20	0.15	0.32
Lift phase	condition	3.1	2,20	0.07	0.24	0.54
	hand	1.3	1,10	0.28	0.11	0.18
	Interaction	0.5	1.3,12.7	0.53	0.05	0.11
Coefficient of cross-correlation	condition	1.9	2,20	0.18	0.16	0.34
	hand	16.0	1,10	**0.003**	0.62	0.95
	Interaction	2.5	2,20	**0.02**	0.20	0.44
Abs. time lag	condition	8.6	1,1,11.4	**0.01**	0.46	0.80
	hand	4.6	1,10	0.06	0.32	0.49
	Interaction	4.6	1,1,11.4	**0.05**	0.31	0.53
Force Parameters						
GF at lift off	condition	0.4	2,20	0.65	0.04	0.11
	hand	3.4	1,10	0.10	0.25	0.39
	Interaction	0.0	2,20	0.95	0.01	0.06
GFmax	condition	7.1	2,20	**0.01**	0.42	0.89
	hand	6.6	1,10	**0.03**	0.40	0.64
	Interaction	1.3	2,20	0.31	0.11	0.24
GFhold	condition	33.1	2,20	**<0.001**	0.77	1.00
	hand	10.5	1,10	**0.009**	0.51	0.83
	Interaction	1.1	1.1,11.4	0.33	0.10	0.16
Safety margin	condition	5.0	1.2,12.0	**0.04**	0.33	0.58
	hand	3.4	1,10	0.10	0.25	0.39
	Interaction	0.7	1.1,11.3	0.43	0.07	0.13

Table 4.3. Statistics values of the main effects of factors 'condition' (M, M+L, M+H) and 'hand' (Less-affected, Affected) on the parameters of the grip-lift task. Effect sizes were estimated by means of partial eta squared values and sensitivity were estimated by observed power.

Post hoc Pairwise comparisons								
			Paired Samples *t*-Test *p*-Value					
Time Parameters	Group	Mean (SD)	M Less	M+L Less	M+H Less	M Aff	M+L Aff	M+H Aff
Preload Phase (ms)	M Less	112 (63)						
	M+L Less	138 (74)	**0.02**					
	M+H Less	162 (97)	**0.01**	**0.04**				
	M Aff	234 (126)	**0.01**	**0.05**	0.15			
	M+L Aff	247 (110)	**0.01**	**0.02**	0.09	0.22		
	M+H Aff	276 (127)	**0.00**	**0.01**	**0.05**	**0.01**	0.057	
Coefficient of cross-correlation	M Less	0.81 (0.06)						
	M+L Less	0.81 (0.07)	0.93					
	M+H Less	0.81 (0.06)	0.42	0.51				
	M Aff	0.71 (0.09)	**0.01**	**0.01**	**0.01**			
	M+L Aff	0.70 (0.09)	**0.003**	**0.003**	**0.002**	0.21		
	M+H Aff	0.68 (0.09)	**0.001**	**0.001**	**0.001**	0.09	0.27	
Abs. Time Lag (ms)	M Less	16 (5)						
	M+L Less	16 (6)	0.85					
	M+H Less	18 (7)	0.09	0.11				
	M Aff	47 (49)	0.06	0.058	0.09			
	M+L Aff	58 (65)	0.06	0.059	0.08	0.08		
	M+H Aff	66 (70)	**0.04**	**0.04**	**0.05**	**0.02**	**0.01**	
			Paired Samples *t*-Test *p*-Value					
Force Parameters	Group	Mean (SD)	M Less	M+L Less	M+H Less	M Aff	M+L Aff	M+H Aff
GFmax (N)	M Less	10.4 (3.9)						
	M+L Less	11.3 (3.7)	0.34					
	M+H Less	11.1 (14.4)	0.24	0.81				
	M Aff	13.0 (4.7)	0.057	**0.01**	0.22			
	M+L Aff	13.9 (4.7)	**0.01**	**<0.001**	0.07	0.13		
	M+H Aff	15.3 (4.8)	**0.01**	**<0.001**	**0.03**	**0.002**	**0.07**	
GFhold (N)	M Less	6.8 (3.3)						
	M+L Less	7.4 (3.0)	0.34					
	M+H Less	7.9 (3.7)	**0.004**	0.46				
	M Aff	9.1 (3.5)	**0.04**	0.08	0.27			
	M+L Aff	10.1 (3.8)	**0.002**	**0.01**	**0.03**	0.07		
	M+H Aff	11.3 (3.9)	**0.001**	**0.001**	**0.01**	**<0.001**	**0.02**	

Table 4.4. Post hoc pairwise comparisons of the parameters of the grip-lift task. There are 15 possible combinations of the factors ‘condition’ (M, M+L, M+H) and ‘hand’ (Less for ‘Less-affected’ and Aff for ‘Affected’).

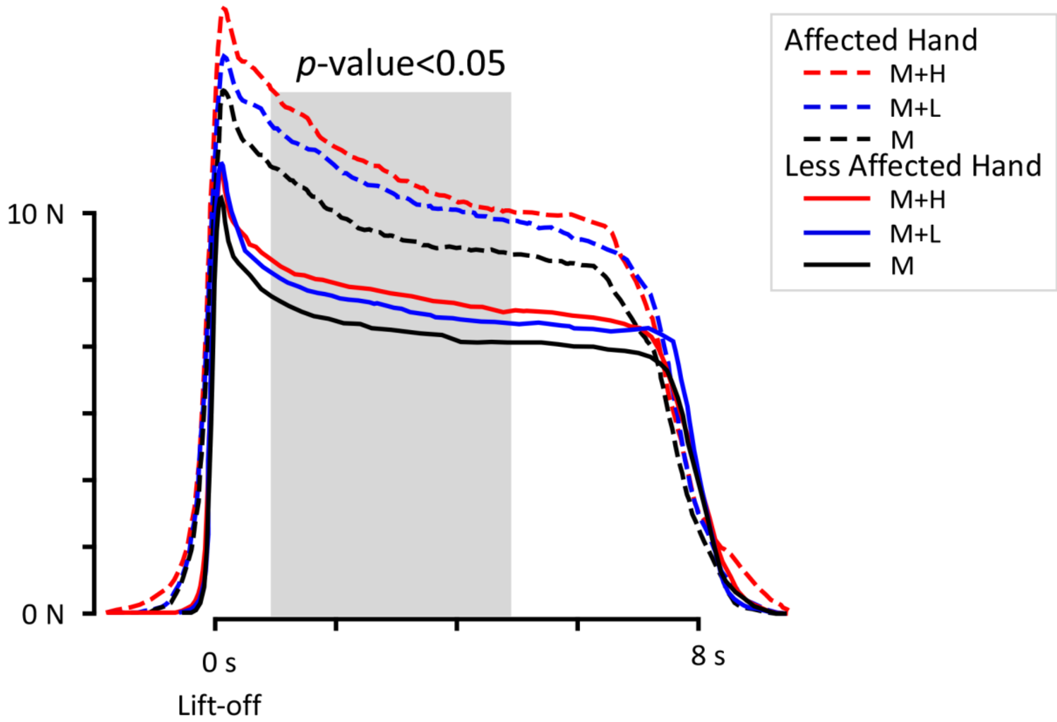

Figure 4.3 Group-level average waveforms of GF obtained in each of the three conditions and the two hands of chronic stroke participants, after realigning trials to the lift-off of the object. The waveforms were compared using a point-by-point repeated-measures analysis of variance with the factors 'condition' and 'hand'. This analysis revealed a significant difference across the three conditions and two hands extending between 1.07 s and 5.18 s after lift-off.

Comparison of the Grip-Lift parameters between chronic stroke and healthy participants

These comparisons are reported in Table 4.5. and can be seen in Figure 4.2. No value obtained through the less affected was significantly different from the dominant hand of healthy participants (all Z-scores were below 0.4 and above -1.4). The values of the preload phase, load phase and the absolute time lag obtained with the affected hand were all significantly higher than those of the dominant hand of healthy participants in every condition. The values of the lift phase were not significantly different between different participants in every condition (-0.1<Z-score<1.8). The coefficient of cross-correlation between the affected hand in the M+L and the M+H conditions were significantly smaller than those in the dominant hand of healthy participants (respective Z-score= 2.1 and 2.4). The values of GFmax and GFhold obtained through the affected hand in the M condition were significantly higher than in the dominants hand of healthy participants in the same condition (respective Z-score = 2.2 and 2.1). Z-scores didn't reveal other difference (all other Z-scores were below 1.8 and above -1.8).

	Less affected Hand			Affected Hand		
Time Parameters	M	M+L	M+H	M	M+L	M+H
Preload Phase	-0.1	-0.1	-0.7	**-2.9**	**-2.1**	**-2.6**
Load Phase	-0.2	-0.1	-0.9	**-2.7**	**-3.9**	**-5.7**
Lift Phase	0.4	-0.1	0.0	0.9	1.1	1.8
Coefficient of Cross Correlation	0.2	0.3	0.3	1.4	**2.1**	**2.4**
Abs. Time Lag	-0.7	-0.8	-1.3	**-2.7**	**-3.4**	**-5.0**

	Less affected Hand			Affected Hand		
Force Parameters	M	M+L	M+H	M	M+L	M+H
GF at lift off	-1.1	-0.7	-0.8	-1.8	-1.5	-1.4
GFmax	-1.4	-0.8	-0.6	**-2.2**	-1.6	-1.5
GFhold	-1.2	-0.6	-0.7	**-2.1**	-1.6	-1.7
Safety Margin	-1.3	-1.3	-1.3	-1.4	-1.5	-1.7

Table 4.5. Value of time and Force parameters computed in Z-score, with reference from healthy participants of our previous study (Chapter III) (Guillery *et al.*, 2017). Values above +2 or below -2 are abnormal.

IV.4. Discussion

In this study, we use a calibrated tool (Chapters II and III) to evaluate cognitive-motor interaction in chronic stroke participants. Importantly, as compared to previous studies using a dual-task paradigm with upper limb movement and cognitive task (Glover *et al.*, 2004; Voelcker-Rehage and Alberts, 2007; Voelcker-Rehage, Stronge and Alberts, 2007; Li *et al.*, 2009; Hesse and Deubel, 2011; Guillery, Mouraux and Thonnard, 2013; Bumsuk *et al.*, 2014; Spiegel, Koester and Schack, 2014; Korotkevich *et al.*, 2015; Maes, Wanderley and Palmer, 2015), we selected our cognitive tasks which were deliberately not related to any known processes involved in the motor task. We assumed that performances of the cognitive tasks in the present study did not involve any motor process and, instead, specifically recruited semantic memory in the M+L condition, and working memory and related executive functions in the M+H condition. For this reason, the differences between the motor and cognitive tasks observed in the present study should not be due to competition for resources specifically involved in motor control.

Chronic stroke participants significantly lengthened the preload and load phases, got a smaller coefficient of cross-correlation and strengthened their grips (GFmax and GFhold) when performing the motor task with the affected hand as compared to the less affected hand. The absolute time lag was also lengthened between the M and M+H conditions with the affected hand. This confirms the significant difference in sensorimotor performances between the two hands of chronic stroke participants with an upper-limb deficit.

There were significant interaction effects between hand and condition factor, in the coefficient of cross-correlation and its absolute time lag, indicating that the more the task is difficult, and with the affected hand, the greater the perturbation.

Irrespective of the hand used and between all conditions, the preload phase and the absolute time lag were lengthened and the GFhold was increased, accordingly to the difficulties of the condition. The GFmax and safety margin were increased between the M and M+H conditions. Increasing the Safety Margin implies increasing the muscular effort required to perform the motor task, and increasing the risk of damaging the manipulated object if it is delicate. Conversely, increasing the Safety Margin reduces the risk of slippage due to variations in grip force, or to the occurrence of an external perturbation. When participants performed the M+H condition, the difference in grip force during the holding phase were significantly greater than when they performed the motor task alone (M condition), indicating that the high-load cognitive task did affect the constancy of the grip force. A possible explanation for the increased Safety Margin could be that it reduced the need to monitor the environment for possible perturbations that could interfere with the object manipulation and require to adjust the grip force (Westling and Johansson, 1984), or to monitor somatic input from the fingertip that could signal slippage of the object (Johansson and Westling, 1987), such as the afferent input that might be generated during partial slip (Johansson and Westling, 1987).

Data obtained through the less affected hand of chronic stroke participants was not different than data of the dominant hand of healthy participants. The cognitive tasks did not appear to exert a stronger effect on motor performance between healthy and less affected chronic stroke hand of participants. However, the values of the preload phase, load phase and the absolute time lag obtained through the affected hand were all significantly higher than those of the dominant hand of healthy participants in every condition. The coefficient of cross-correlation obtained through the affected hand in the M+L and the M+H conditions were significantly smaller than those in the dominant hand of healthy participants.

One of the most striking effects is shown in Figure 4.3. The group-level average waveforms of GF after realigning trials to the lift-off of the apparatus increase according to the hand use and according to each of the three conditions, with scaling with the difficulty of the task.

Cognitive tasks specifically recruiting working memory and semantic memory interact with the planning and the on-line control of the fine grip manipulation in chronic stroke participants. While the less affected hand of chronic stroke participants have a similar behaviour than the dominant hand of healthy participants, the affected hand demonstrated an alteration of predictive and reactive processes even greater than the dominant hand of healthy participants.

Assessing motor performance under cognitive load is proven to be a sensitive mean to estimate motor abilities, especially dual-tasks involving manual dexterity, and their evolution in dual-task situations in healthy and chronic stroke participants. It could be of interest to assess the performance of other participants with other neurological disorders.

CHAPTER V. Discussion and perspectives

In this thesis, we used cognitive-motor paradigms to examine whether dexterous manipulation, a highly habitual and seemingly automatic behaviour, involves high order cognitive functions in healthy and chronic stroke participants.

The clinical usefulness of assessing the performance of the grip-lift task to evaluate motor function in healthy participants and with neurological diseases is largely recognised (Nowak, Glasauer and Hermsdörfer, 2004; Nowak and Hermsdörfer, 2006a; Nowak, 2008). However, these clinical assessments are always performed in isolation. Indeed, most of the main evaluation of the hand and upper limb function focus on the mechanical properties of the behaviour, omitting other aspects, such as cognitive function. Simultaneous execution of cognitive and sensorimotor tasks is critical in daily life. Since dual-tasking is being studied by broad fields of professionals with different domains of expertise, we try to frame the different notions involved in the thesis by specifying consensual definitions, in chapter I. We design a dual-task paradigm to examine dual-tasks interferences, in healthy participants in chapter II & III, and in chronic stroke participants in chapter IV. Importantly, we design our cognitive-motor interference paradigm with the latest recommendations in dual-tasks design (Schaefer, 2014; Mcisaac, Lamberg and Muratori, 2015; McIsaac *et al.*, 2018). Our motor task is a pure grip, lift and hold task that required the minimum distance of reaching and thus minimized the necessity of control on trunk, shoulder and arm muscles. The cognitive tasks are meant to be the most simple in terms of the complexity of behaviour and involved mental processes. In experiment 1 (Chapter I), our cognitive task is a complex visual researching and counting task. We designed this task to challenge our motor task with a strong cognitive load. In experiment 2 and 3 (Chapter III & IV), we selected our new cognitive tasks to manipulate the cognitive load by recruiting semantic memory and working memory.

V.1. The contribution of this work to the field

In this section, we expose and discuss the main results arising from our different studies. Perspectives for future research are also exposed.

In this thesis, our motor task was always a precision grip, lift, hold and replace task, guided by an auditory signal. The precision grip task can be split into these intermediate phases: reaching, preloading, loading, lifting, holding, replace, unloading and releasing phases (Johansson & Westling 1984; Johansson et al. 2010). In our experiments, we focus our analysis on the grip-lift and hold of the apparatus. Thus, at least procedural memory, tactile and proprioceptive perceptions and in a lesser extent visual and auditory perceptions are involved in this motor task. The fine control of precision grip relies on feedforward and feedback mechanisms (Johansson and Westling, 1987). Although, the CNS orchestrates these processes with internal models reflecting anticipatory feedforward commands (predictive mechanisms) and sensory feedback loops (reactive mechanisms) (Wolpert and Ghahramani, 2000).

As expected, in our dual-tasks healthy adults and chronic stroke participants irrespective of the hands used, significantly lengthen their preload phase and strengthen their grip throughout the grip-lift task. These differences were scaled to the needs in cognitive resources. Preload phase and GFhold were significantly increased in both hands of chronic stroke participants, with the strongest increase with the affected hand and the increasing difficulty of conditions. The load phase is decreased in healthy participants in M+H condition as compared to the other conditions. In chronic stroke participants, the load phase, the coefficient of cross-correlation, the GFmax were increased with the affected hand irrespective of the conditions. The GFmax and the safety margin were increased from the M condition to the M+H condition.

Overall, the cognitive tasks did not appear to exert a stronger effect on motor performance between healthy and the less affected hand of chronic stroke participants.

In healthy participants, we argue that the increase in preload phase in the dual-task conditions is due to the fact that cortical processing of the somatosensory inputs generated by the contact and friction of the finger with the object is modulated by the availability of working memory resources (Guillery *et al.*, 2017)(ChapterIII). This view is also supported by the results of previous studies showing that movement planning requires working memory resources and can interfere with concurrent cognitive processing (Glover *et al.*, 2004; Liu, Chua and

Enns, 2008; Enns and Liu, 2009; McIntosh, Mulroue and Brockmole, 2010; Hesse and Deubel, 2011; Gilster, Hesse and Deubel, 2012; Spiegel *et al.*, 2012; Spiegel, Koester and Schack, 2013; Gunduz Can, Schack and Koester, 2017). In chronic stroke participants, the general increase in time parameters (preload phase and absolute time lag) and force parameters (GFmax, GFhold and the safety margin) is assumed to be the result of an alteration of integration into the internal model of the sensory signal feedback arising from the initial contact with the apparatus. It has already been demonstrated before in a grip-lift oscillatory movement (McDonnell *et al.*, 2006). Thus, in dual-task conditions, the shortening of working memory resources led to an even stronger impact on the preload phase and the absolute time lag, and the GFmax, GFhold and safety margin, with the increasing difficulty of the task (Chapter IV). This effect indicates that these parameters involve processes that are not purely automatic and, instead, require higher-order cognitive resources.

Under cognitive load, the load phase and the absolute time lag were decreased, and the lift phase increased in healthy participants performing the M+H condition, and the coefficient of cross-correlation was not affected. We assume that when performing a demanding cognitive task, healthy participants may further rely on these automatic processes to reduce the need for higher-order cognitive resources, leading to a reduction of the time-lag between grip and load forces, and a reduction of the total duration of the Load phase (chapter IV). While in chronic stroke participants the load phase was greater with the affected hand than with the less affected hand, and than the dominant hand of healthy participants. In chronic stroke participants, the load and lift phases and the coefficient of cross-correlation were about the same across the different conditions. We hypothesise that these parameters are less dependent on higher-order cognitive resources and may involve automatic processes.

The grip force is thought to be adjusted through reactive mechanisms relying on tactile feedback (Johansson & Westling 1984). One possible explanation to the increased grip force (GF at lift off, GFmax, GFhold) is that participants anticipated the interference of the concurrent cognitive task by increasing the safety margin and, thereby, reduced the risk of letting the object slips because of less optimal planning and/or fine-tuning of the grip force. Another complementary explanation could be that this increase compensated a reduction in the coefficient of friction between the fingertips and the manipulated object. Indeed, the difficulty of the dual-task could have induced an autonomic response leading to a change in skin fingertip moistness, a factor known to crucially determine the coefficient of friction (Bleyenheuft et al. 2009; André et al. 2010). Even if we did observe a significant difference in the coefficient of friction across hands of chronic stroke participants, the coefficient of friction did not change before and after recording session in our experiments with healthy and chronic stroke participants. Thus, excessive GF can be attributed to impaired sensory feedback (Blennerhassett et al. 2007) and the alteration of temporal coupling was attributed to deficits in developing internal models or alteration of feedback transmission. Indeed, stroke survivors with mild to moderate sensorimotor dysfunction of the hand often apply excessive grip force. This has been interpreted to reflect a strategic response of the motor system to guarantee a stable grasp in the pathological state (Hermsdörfer et al., 2003; Nowak et al., 2003). It is argued that the consequences of cortical and subcortical pathology on manual dexterity, are partly compensated for by new, less flexible default strategies (Wiesendanger and Serrien, 2001).

When peripheral sensory information is impaired, the lack of sensory feedback transmission and processing must be compensated by an increased collection of other sensory information. This is shown in healthy participants with local anaesthesia of the index and thumb (Augurelle et al. 2003) and in participants with peripheral nerve lesions (Afifi et al. 2012; Thonnard et al. 1997). In chronic stroke participants, parameters of the grip-lift task are altered due to the no longer optimal adjustment of grip force (Chapter IV). This is consistent with previous studies showing that patients with cortical, subcortical and cerebellar stroke exhibit alteration of forces scaling and deficits in the temporal coupling of the grip and load forces (Hermsdörfer *et al.*, 2003; Nowak, Hermsdörfer and Topka, 2003; Nowak, 2006; Anens, Kristensen and Häger-Ross, 2010). Both predictive and reactive controls of the movement are perturbed (Dispa et al., 2014; Bleyenheuft and Gordon, 2014). Actually, the predictive mechanism is present but altered in the paretic hand (Takahashi & Reinkensmeyer 2003; Raghavan et al. 2006). In the grip-lift task, due to both sensory and motor deficits, the timing and scaling of grip force, and coupling between grip and lift forces, are also significantly altered. Even in the presupposed unaffected hand, ipsilateral to the lesion, in patients with subcortical middle cerebral artery stroke (Quaney et al. 2005; Nowak et al. 2007).

To sum up, the precision grip-lift task is a fast learned skill and remains stable across repetitive trials (Johansson and Westling, 1988a; Flanagan, Bowman and Johansson, 2006). Healthy and chronic stroke participants had to use the same object and perform the same movement in each condition. However, in dual-tasks, they took more time to conform their fingers on the object. Additionally, the more demanding was the cognitive task the more they strengthened their grip on the object. In the low load dual-task healthy and chronic stroke participants had to remember their alphabetical order only at the end of the trial, after performing the grip-lift task, however, the early phases of the grip-lift task were still altered, i.e. the preload and load phases. When participants were holding the apparatus, they had enough time to collect sensory afferent information and should have released their grip on the object just enough to keep it in the air, but they did not. If predictive force scaling and actual object weight does not match, the online motor corrections, rapidly implemented to downscale forces, will also downscale weight estimation in a proportional manner (van Polanen and Davare, 2015b). However, it was not the case in our experiments (Chapters III & IV), thus, both the planning and the online control of the movement were disturbed by the concurrent cognitive tasks. These findings are consistent with studies that have already reported the effects of semantic on grasping behaviour (Glover, 2002; Glover *et al.*, 2004; Tiainen *et al.*, 2017). Besides it was no intended congruence in motor and cognitive tasks in our studies, the simple knowledge that there will be a later concurrent semantic task affects the dexterous manipulation.

Ageing

Healthy ageing is associated with alteration of the sensory and motor systems, processing capacity, sensitivity to distraction and cognition in general (de Dieuleveult et al. 2017). The more unexpected outcome of the study in healthy participants (Chapter II) is the absence of age effect in cognitive-motor interaction task, between the three conditions. The absence of age interaction with the difficulty of the tasks is probably due to the fine calibration of the difficulty of the task adapted for performances of each participant (Figure 4.1). As expected, the Preload phase was longer in the older group as compared to the middle age group and the absolute time-lag was greater in the older group as compared to the young group.

In a further study, increasing the difficulty of the cognitive or motor tasks over the limits of each participant could be of interest to compare the number of mistakes made by each group. Even if it risks leading to more participant frustration it will be a more sensitive way to assess cognitive-motor interaction. With an increasing difficulty of cognitive and motor tasks, we expected that healthy older participants and neurological disease participants would be more disturbed than young and middle age participants. The requirement of cognitive resources in more difficult tasks could even prevent the performance of one or both tasks.

With the ageing of the population, there is growing morbidity among ageing adults (Hoffman *et al.*, 2017). The heterogeneity of older adult persons ranges from clinically diagnosed dementia, to the disease-free elder including also those under the relatively new term of mild cognitive impairment (MCI). MCI refers to those older people who do not meet the criteria for dementia, but still has substantially cognitive impairments as compared to healthy older adults (Aggarwal *et al.*, 2006). It would be of interest to test these other populations to assess their potential limitations in dual-tasks activity.

Neural correlates of dexterous manipulation and dual-tasking

This section is a brief review of the literature about the neural correlates involved in dexterous manipulation behaviours and in dual-task paradigms.

In our experiments, the behavioural difference between preload, load and lift phases highlight their differences in terms of motor control and their neuronal subtracts. Functional neuroimaging studies using the grip-lift task revealed the activation of a large number of cortical areas (Ehrsson *et al.*, 2000; Kuhtz-Buschbeck, Ehrsson and Forssberg, 2001; Cavina-Pratesi *et al.*, 2018). Indeed, the activity of the primary and supplementary motor cortex became stronger and more widespread when finger movements are performed at increasing levels of force, and also with increasing demands on dexterous control. The neural correlates of the planning of dexterous manipulation included the dorsolateral prefrontal cortex, basal ganglia, anterior cingulate cortex, posterior medial parietal area, superior parieto-occipital cortex, anterior intraparietal sulcus and middle intraparietal area. The online control of dexterous manipulation includes the sensorimotor cortex, the cerebellum, the supra-marginal gyrus and the superior parietal lobule (Glover, Wall and Smith, 2012). The Precision grip-lift task specifically recruits the anterior intraparietal sulcus (Ehrsson *et al.*, 2000; Cavina-Pratesi *et al.*, 2018). Its activation increases with the degree of precision required, even when the number of digits utilized is constant, and also with the increasing number of digits involved in the task (Cavina-Pratesi *et al.*, 2018). The grip-lift task which requires the computation of grip and load forces specifically recruits the anterior intraparietal sulcus, the dorsal premotor cortex and supplementary motor area. The scaling of the grip force level and the dynamic grip and load forces coupling are already known as dissociable aspects of grip force control (Hermsdörfer et al. 2005; Bleyenheuft & Gordon 2014). The anterior intraparietal sulcus is involved in the reactive online adjustment of grip force during object manipulation, the ventral premotor cortex in the predictive scaling of grip force, (Dafotakis *et al.*, 2008), while the dorsal premotor cortex is involved in the control of basic movement kinematics (van Polanen and Davare, 2015a) and visually guided movements (Johnson et al., 1996). This neural network for dexterous manipulation is robust with only minor alterations even after the acute loss of tactile information from the fingers (Pavlova *et al.*, 2015).

There is a consensus in the literature that the cerebellum plays a major role in acquiring and storing internal models, including the coupling of grip and load forces (Wolpert, Goodbody and Husain, 1998; Wolpert and Flanagan, 2001; Kawato *et al.*, 2003). Several brain imaging studies support the idea that the cerebellum is the anatomical correlates of such internal models (Kawato *et al.*, 2003; Bursztyn *et al.*, 2006), and patients with cerebellar damage exhibited clear deficits in the coupling between grip force and load force (Hermsdörfer et al. 2004; Hermsdörfer et al. 2005). Basal ganglia disorders are associated also with deficits of sensorimotor integration (Nowak and Hermsdörfer, 2006b).

The prefrontal cortex is strongly associated with executive function and specificity of various cognitive functions, such as cognitive control and decision making. Two distinct functional-anatomical networks were revealed within the prefrontal cortex. One is associated with cognitive control (response inhibition, conflict monitoring, and switching), which included the dorsolateral prefrontal cortex and anterior cingulate cortex. The second is associated with value-based decision-making, which included the orbitofrontal, ventromedial, and fronto-polar cortex (Watanabe and Funahashi, 2018). By contrast, regions in the ventral prefrontal cortex were required for decision-making. The dorsolateral prefrontal cortex appears to be critical for the smooth execution of complex behaviours that consist of multiple sub-goals, by orienting and pacing focus on a current goal (Domenech and Koechlin, 2015). The fronto-polar prefrontal cortex juggles between several, temporally distant goals by guiding the allocation and reallocation of resources to each goal (Mansouri *et al.*, 2015).

In experimental psychology, behavioural evidence indicates that not only two similar tasks but also two dissimilar tasks can interfere with each other. Similar tasks still tend to interfere with each other more strongly than dissimilar tasks (Bourke, 1997). Recent reviews failed to determine a unitary and consensual model to explain dual-task interaction (Watanabe and Funahashi, 2014, 2018). The fact that specific cortical areas are selectively activated in dual-task additionally to brain areas activated in single-task performance, is still under debate. There is no specific dual-task area identified in the brain yet (Leone *et al.*, 2017). Every study trying to make assumptions about the specific role of specific brain area have to face the fact that the human brain is highly individual (Valizadeh *et al.*, 2018), thus making hard to generalize any common role of small brain area in human.

Altogether these findings suggest that dual-task interactions are actual competitions for the same neural substrate between the different processes involved in the different subtasks of each behaviour at a given time in a given context. More studies are needed to explore the dual-task phenomena and the causal links between the different brain area involved still need to be established.

Cognitive-motor interaction in other experimental settings

Now that the CMi in healthy and chronic stroke participants is more outlined, it could be of interest to include study by study, one by one other experimental setting. For example, the *stable* motor grip-lift task could be substituted with a sensorimotor adaptation task, e.g. a constraint reaching movements within force fields (Shadmehr and Mussa-Ivaldi, 1994), to investigate motor skill learning in a more challenging situation with a dual-task paradigm. If a skill is mastered or *automatized*, it will no longer require as many cognitive resources as before, allowing to perform another task at the same time (Wulf, McNevin and Shea, 2001; Reuter *et al.*, 2014). Neuroimaging data revealed that all parts of the motor networks reduce their activity and strengthen their functional connectivity with increased in expertise or *automaticity* (Wu, Kansaku and Hallett, 2004; Wu, Chan and Hallett, 2008). We hypothesize that CMi effects will be inversely proportional to the participants' expertise in the motor task. Perturbation of the motor task will be even more pronounced with the increasing difficulty of the task and in participants with neurological disorders, especially with the affected hand and in the first trials when a novel perturbation occurred.

In everyday life, we manipulate many new objects of different size and weight, with sometimes some unexpected changes. In further studies it could be of interest to build a more suited paradigm to evaluate the predictive or reactive processes involved in precision grip behaviour, as the brisk loading of a handheld object paradigm, under predictable or unpredictable conditions (Johansson & Westling 1988b; Bleyenheuft et al. 2009; Dispa, et al. 2014). This could be achieved with a device that can alter it weight before and during its manipulation. Given that our cognitive-motor paradigm involved visual displays, adaptations are required. We could train our participants to perform the different brisk loading tasks without visual feedbacks or change the modality of presentation of memory set and memory cue of our cognitive tasks from visual stimuli to auditory stimuli. We hypothesize greater alterations of performances with the increasing difficulty of the dual-tasks.

To increase the precision of our measured parameters, such as the coefficient of friction static of each participant, it could be of interest to measure online both the apparatus position, speed and acceleration in three dimensions of space. It would enable the detection of potential slip or partial slips. Indeed partial slips play an important role in fingertip slip detection and the central nervous system relies on them to adjust grip force during object manipulation (Barrea *et al.*, 2018). The used apparatus could be instrumented with axis force and torque sensor as described in a recent study (Barrea *et al.*, 2016). Since the apparatus (manipulandum) used in our experiments required several devices to be functional, it could be of interest to use a lighter set-up in further experiments.

V.2. Limitations

In this section, limitations arising from our different studies are exposed and discussed.

First, the broad context of this work required to frame a consensual theoretical background. Thus, we aimed to provide a common language for scientists and clinicians (from engineers, physicists, neuroscientists, to neurologists, physicians, physiotherapists, occupational therapists and nurses) concerned with motor control, cognitive control, their interactions and their implications in assessment and rehabilitation. This is proposed in chapter I. We tried to set a consensual framework and followed the latest recommendation in the design of dual-task paradigms. In so doing, we might have missed some critical theoretical or clinical notions that could guide us to design our dual-task paradigm. We have excluded parts of scientific literature in which dual-tasks with obvious temporal overlaps of two task processes, as in dual-task switching and dual-tasks with explicit associations of the different tasks, as in bimanual dual-tasks. We also excluded motor skill learning studies or neurodegenerative studies, to assess *stable*, non-evolutive tasks behaviours between each other. Without these precautions, the investigation of dual-tasks interferences could have led to complex, uncontrolled or even inexplicable interaction effects due to the multiplication of possible interacting processes involved in the different tasks.

In chapter II, the cognitive task consisted of a complex visual-research and counting task. The major limitation was that we did not know exactly which were the cognitive processes involved in the cognitive task and furthermore how they interacted with the grip-lift task. Thus, we changed the complex cognitive task with well-known and more controlled working memory tasks, leading to our next experiment, in which participants respectively recruited semantic and working memory. The rationale for restricting the cognitive processes involved in the cognitive tasks is due to the extensive amount of uncontrolled cognitive processes that could be involved. In our first experiment, the cognitive task consisted in performing a complex visual search and counting task. This complex cognitive task can be split into several subgoals, in which visual scanning, memorization and counting, thus recruiting many cognitive processes such as selective, focused and divided attention, visual perception, recognition, working memory, executive functions, among others, the whole submit to the pressure of temporal stress. In the second and third studies, we exploited a cognitive task which minimizes the involvement of motor control and motor imagery. We used the model of Lavie (Lavie and De Fockert, 2005) to modulate the executive control of attention with a working memory task. Actually, the cognitive task was inspired by an experiment of De Focker (de Fockert *et al.*, 2001). In the cognitive tasks, participants had to keep a list of letters in memory during the actual grip-lift task. In this memory rehearsal task, we substitute the number by letter. Indeed an increasing number of studies demonstrated that several aspects of word and number representations can affect motor behaviour (Andres, Olivier and Badets, 2008). For example, our ability to grasp an object is overestimated (or underestimated) when the object is preceded by the presentation of small (or large) numbers. Such a bias is not observed when the object is preceded by the presentation of the first (or last) letters of the alphabet (Badets *et al.*, 2007). Precision grip movements were initiated faster than whole-hand grips after the presentation of a small number and the reverse after the presentation of a large number (van Dijck, Fias and Andres, 2015). However, according to Baddeley, working memory rehearsal is associated with frontal networks such as Broca’s area (Baddeley and Hitch, 2018). Actually, the phonological loop can be divided into a phonological short-term store, which is said to be linked with the inferior parietal cortex, and an articulatory subvocal rehearsal process relying on brain areas necessary for speech production, i.e. Broca's area, the supplementary motor association area and possibly the cerebellum (Müller and Knight, 2006). This subvocal rehearsal process may be the mental process that interferes with the reactive online control processes of the grip-lift task.

A limitation in our studies is the relatively small number of participants. We recruited 18 participants in Chapter II, 37 participants in Chapter III and only 11 participants in chapter IV. However, power tests performed on these data and revealed good or very good power on the main significant results. Since these results are encouraging, we are confident with the fact that the potential inclusion of more participants will lead to the same pattern of results.

Since our sample of participants was selected from adults living at home, and sometimes acquaintances, they may represent a healthier and more educated older adult cohort than those living in other communities, who are of equivalent age.

Another main limitation in chapter IV is the heterogeneous lesions localizations (cortical, subcortical) and aetiologies (large arteries, lacunar infarcts, intracerebral haemorrhages) of included chronic stroke participants. This heterogeneity might have increased the inter-individual variability in behaviour. Nonetheless, this relative heterogeneity may be considered as a strength, since they can be regarded as a more representative real-life group of chronic stroke participants. To unveil the links between specific CNS lesions and behavioural deficits in stroke participants, further studies should include participants with more confined and specific lesions.

The following exposed limitations may be regarded as being more trivial, but they give us the opportunity to open other perspectives for research.

In precision grip behaviour, when a participant is instructed to focus on object movements rather than on finger movements, his control of the task is more effective (Rossettini *et al.*, 2017). These findings are explained by the facts that information stemming from vision or in a lesser extent audition, are less prone to interact with motor processing, than information stemming from as proprioception and kinesthesis, which intrinsically rely on motor processing (Wulf, Shea and Park, 2001; Wulf, 2013). In Dual-task paradigms, the task that is perceived as the more difficult or with the higher threat is the more likely to be prioritized (Yogev-Seligmann, Hausdorff and Giladi, 2012). In our experiments, even if the participants were not instructed to prioritize one task over another, we still asked deliberately our participants to stare at a screen while performing the motor task, for the sake of equivalent visual conditions in our different conditions. When asked informally about their strategy, participants tend to report that they focus on the cognitive task. In further studies, a more formal questionnaire should be proposed to objectively report the participants’ strategy use to cope with the dual-task activity.

In our experiments, all participants lack visual feedback of their hand and the object to grasp. Although, in everyday life, vision plays a major role in the programming and control of our movements (Goodale and Humphrey, 1998; Dispa *et al.*, 2014). In all conditions of each experiment, we ask participants to stare at a fixation cross to minimize the visual perception of the apparatus and thus allowing us to compare similar behaviour between conditions and experiments. However, we didn't cover the hand and the apparatus. Consequently, we cannot provide eventual onsets of eye saccades toward the object or the hand. Anyway, participants may also have information about their hand and the apparatus localisations in peripheral vision, especially when there were no high cognitive demands. Using an eye-tracker to control eyes movements could be of interest. Moreover, eye-trackers can also allow us to implement pupillometric measurement, an efficient technic to evaluate cognitive effort (Piquado, Isaacowitz and Wingfield, 2010; van der Wel and van Steenbergen, 2018).

Body posture (Dispa *et al.*, 2014), wrist position (Bensmail *et al.*, 2009; Ambike *et al.*, 2014) and positioning of fingers (McDonnell *et al.*, 2005) critically affect grip-lift behaviour. In our experiments the investigator monitored the participants' behaviours, limiting or correcting the more obvious parasite or awkward trunk, hands, head or eyes movements, despite they were not strictly and objectively assessed. In further studies, participants may be a videotaped while performing the different experimental conditions. Trials with unexpected behaviours could be carefully examined a posteriori and eventually be rejected.

Another common drawback of additional control technologies is the constraint on participants' movements, making them uncomfortable and also leads them to unusual behaviours. This leads to another drawback common to every research aiming behavioural data: the almost unavoidable choice between carrying out an experiment strictly controlled in an artificial laboratory environment or in an unconstrained everyday life environment. Experiments in a laboratory provide objective and quantitative data about thoroughly manageable and reproducible tasks, while everyday life activities are more spontaneous but hardly controllable. Indeed, there are differences between what a person can do in a standardized environment, without the barriers or facilitators of the person's usual environment, and what a person actually does in the current or usual environment, with all barriers and facilitators in place (World Health Organization, 2011a). A key to solve this issue may be virtual reality. Recent meta-analyses demonstrate that virtual reality rehabilitation programs are more effective than traditional rehabilitation programs for physical outcome development (Lohse *et al.*, 2014; Howard, 2017). This kind of device may be an effective intervention, in a safety configuration which could not be achievable in other modalities of treatment. Participants can perform several practice behaviours while interacting with the computer-simulation of an environment that imitates a physical presence in real or imagined worlds. It is reasonable to think that a grip-lift apparatus to assess dexterous manipulation and motor coordination, and a portable eye-tracking system to assess cognitive effort, can be implemented in such an environment.

Given that stroke survivors tend to overestimate their own, and that their performances in clinical tools are reported to be worse than with everyday tools activities (Schuling *et al.*, 1993; Shih *et al.*, 2009), it could be of interest to assess GF-LF coupling when performing more meaningful behaviours. A simple adaption of the grip-lift task can be achieved by manipulating more meaningful, useful tools or everyday life objects, by using force sensors fixes on the fingertips or even glove fitted with sensors (Eidenmüller *et al.*, 2014) rather than manipulating an instrumented apparatus. The inevitable drawback of this kind of technic is the change of contacts between fingers and manipulated objects.

V.3. Evaluation of dual-tasks activity

In this thesis, we designed a paradigm to test dexterous manipulation in dual-task situations. However, we did not assess formally the reliability and validity of our protocol. Moreover, using our protocol requires expensive and cumbersome laboratory equipment, and taking together preparation, recording and analysis take several hours. Since the set-up of our experiments can hardly meet the psychometric qualities of good assessment scale (Souza *et al.*, 2017), we do not recommend to use it in routine clinical practices to evaluate dual-task activities. Box 5.3. demonstrates the most used psychometric qualities met in the literature (Mokkink *et al.*, 2010). However, it brings us valuable and precise data about dual-task activity in healthy and chronic stroke participants. To our knowledge, it is the most accurate assessment of dexterous manipulation, CMi and dual-task activity of everyday life.

Reliability:

Ability to produce consistent results when repeatedly measuring the same outcome.

- **Test-Retest:** Testing and then retesting the same set of people on the same set of test items to examine the consistency of their responses.
- **Inter-rater:** Different trained ratters get consistent results when using the same scale on same set of people.
- **Internal Consistency:** Cohesiveness of a scale's items. Do all the items in the scale measure the same characteristic or concept? Can they be logically grouped together?

Validity:

The scale correctly captures the concept of interest.

- **Internal Validity:** The scale correctly measures what it intended to measure.
- **External Validity:** Ability to create results that can be generalizable.

Invariance:

Score obtained by an individual at the different items is influenced only by his ability and the difficulty of the items and not by his personal characteristics (sex, age, etc.).

Unidimensionality:

The scale measures only the target variable without interference of other characteristics of the sample.

Sensitivity:

Sensitive to change. Detection of clinically significant changes as a result of treatment or the evolution of the disease itself.

Linearity:

The scale as a constant unit of measurement; the distance between two consecutive categories is equivalent on the whole scale.

Feasibility:

The scale is fast to perform and interpret. It requires little or no specific material.

Box 5.3. Most Commonly encountered psychometric qualities

Actually, scales measuring upper-limb activities exist in the literature, however, scales meeting all the psychometric qualities are scarce. Most of them are not unidimensional or Linear (Santisteban *et al.*, 2016). The strongest level of measurement quality and clinical utility was demonstrated for Fugl-Meyer Assessment, Action Research Arm Test, Box and Block Test, Chedoke Arm and Hand Activity Inventory, Wolf Motor Function Test and ABILHAND (Aguilar, Duran and Cubero, 1977) We recommend to use the ABILHAND scale for chronic stroke participants to assess the activity domain of the ICF after a stroke (Penta *et al.*, 2001).

To our knowledge, there is only one short test to evaluate in dual-task activities for the upper-limb yet (Toosizadeh *et al.*, 2016). This test consists of performing repetitive elbow flexion at maximum pace, once solely, and once while counting backward by one. It lasts only 20s for the participants, its score consists of eight different quantitative parameters strongly correlated with another upper-limb reference scale (Toosizadeh *et al.*, 2016). Incidentally, we all have the vision of this elderly person who serves tea in different cups. When asked a question, she stops pouring tea as soon as she wants to answer. As the famous “Stops walking when talking” test for the lower limb exists, why not propose a “Stops pouring when talking” test for the upper limb?

To evaluate the possible effects of a rehabilitation program, a complete evaluation of the hand should be considered, following the ICF model with its different domains, function, activity, and participation. Our dual-task paradigm can be used as a tool to evaluate cognitive-motor interaction. It could be conducted before and immediately after rehabilitation, as well as 1, 3 and 6 months after rehabilitation, to evaluate the possible effects of the rehabilitation over time on the various parameters tested. It will objectively quantify the effect of cognitive-motor interaction in chronic stroke participants.

Dual-task evaluation can provide us with information about the participants’ activity domain of the ICF. A next step would be to evaluate participation restriction. The difficulty of this evaluation consists in the multimodal aspect of participation itself and the fact that a social environment is very unlikely to be evaluated with tests with strong and objective psychometric qualities (Cordier *et al.*, 2015). Another limitation is that activities and participation evaluations are often merged (Tse *et al.*, 2013). This is why very few tests exist in the literature. The PM-Scale has good psychometric qualities and provides accurate measures of in community-dwelling stroke survivors in Africa (Kossi *et al.*, 2018). It could be of interest to adapt this questionnaire in other contexts.

Conclusion

The aim of this thesis was to evaluate the dual-task interference in healthy and chronic stroke participants. Cognitive task specifically recruiting working memory interacts with the planning and the online control of the fine grip manipulation. Thus, dexterous manipulation is not an automatic behaviour and requires high-level cognitive process at some critical times. Since dual-tasks are omnipresent in everyday life, they cannot be omitted in the functional evaluation of the upper limb. Assessing motor performance under cognitive load might be a more sensitive approach to actually assess motor function, motor-cognitive dual-task activity and their impacts in real life situations.

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Appendix A: MMSE questionnaire - Folstein test (Folstein et al., 1975)

The Mini-Mental State Examination (MMSE) is a short questionnaire of 30-point that is used extensively in clinical and research settings to measure cognitive impairment. It is also used to assess the course of cognitive changes. Administration of the test takes between 5 and 10 minutes and examines functions including attention, calculation, recall, language, ability to follow simple commands and spatial and temporal orientation. A copy of the questionnaire and its supplement are display in Figure A.1. and A.2.

One of the advantages to the MMSE includes requiring no specialised equipment or training for administration. It has both validity and reliability for the diagnosis and longitudinal assessment of Alzheimer's disease. Any score greater than or equal to 24 points (out of 30) indicates a normal cognition. Below this, scores can indicate severe (≤9 points), moderate (10–18 points) or mild (19–23 points) cognitive impairment. However, the raw score may also need to be corrected for educational attainment and age(Crum, 1993; Crum et al., 1993). Low to very low scores correlate closely with the presence of dementia, although other mental disorders can also lead to abnormal findings on MMSE testing. The presence of purely physical problems can also interfere with interpretation if not properly noted; for example, a participant may be physically unable to hear or read instructions properly, or may have a motor deficit that affects writing and drawing skills.

Mini Mental State Examination (MMSE) (Version consensuelle du GRECO)

Orientation **/ 10**

Je vais vous poser quelques questions pour apprécier comment fonctionne votre mémoire.
Les unes sont très simples, les autres un peu moins. Vous devez répondre du mieux que vous pouvez.
Quelle est la date complète d'aujourd'hui ? ______________________________

Si la réponse est incorrecte ou incomplète, posées les questions restées sans réponse, dans l'ordre suivant :

1. En quelle année sommes-nous ?
2. En quelle saison ?
3. En quel mois ?
4. Quel jour du mois ?
5. Quel jour de la semaine ?

Je vais vous poser maintenant quelques questions sur l'endroit où nous trouvons.

6. Quel est le nom de l'hôpital où nous sommes ?*
7. Dans quelle ville se trouve-t-il ?
8. Quel est le nom du département dans lequel est située cette ville ?**
9. Dans quelle province ou région est située ce département ?
10. A quel étage sommes-nous ?

Apprentissage **/ 3**

Je vais vous dire trois mots ; je vous voudrais que vous me les répétiez et que vous essayiez de les retenir car je vous les redemanderai tout à l'heure.

11. Cigare		Citron		Fauteuil
12. Fleur	ou	Clé	ou	Tulipe
13. Porte		Ballon		Canard

Répéter les 3 mots.

Attention et calcul **/ 5**

Voulez-vous compter à partir de 100 en retirant 7 à chaque fois ?*

14.	93
15.	86
16.	79
17.	72
18.	65

Pour tous les sujets, même pour ceux qui ont obtenu le maximum de points, demander :
Voulez-vous épeler le mot MONDE à l'envers ?**

Rappel **/ 3**

Pouvez-vous me dire quels étaient les 3 mots que je vous ai demandés de répéter et de retenir tout à l'heure ?

11. Cigare		Citron		Fauteuil
12. Fleur	ou	Clé	ou	Tulipe
13. Porte		Ballon		Canard

Langage **/ 8**

Montrer un crayon. 22. Quel est le nom de cet objet ?*
Montrer votre montre. 23. Quel est le nom de cet objet ?**
24. Ecoutez bien et répétez après moi : « PAS DE MAIS, DE SI, NI DE ET »***

Poser une feuille de papier sur le bureau, la montrer au sujet en lui disant : « Ecoutez bien et faites ce que je vais vous dire :
25. Prenez cette feuille de papier avec votre main droite,
26. Pliez-la en deux,
27. Et jetez-la par terre. »****

Tendre au sujet une feuille de papier sur laquelle est écrit en gros caractère : « FERMEZ LES YEUX » et dire au sujet :
28. « Faites ce qui est écrit ».

Tendre au sujet une feuille de papier et un stylo, en disant :
29. « Voulez-vous m'écrire une phrase, ce que vous voulez, mais une phrase entière. »*****

Praxies constructives **/ 1**

Tendre au sujet une feuille de papier et lui demander : 30. « Voulez-vous recopier ce dessin ? »

Figure A.1. Copy of MMSE Questionnaire in French.

« FERMEZ LES YEUX »

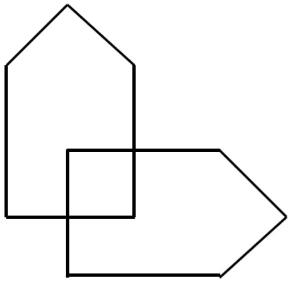


Figure A.2. MMSE questionnaire supplement showing the cue sentence and drawing to reproduce in the test.

Appendix B: ABILHAND questionnaire (Penta et al., 2001)

(http://www.arsalis.com/rehab-scales/abilhand-instructions.html)

The ABILHAND questionnaire is a short questionnaire evaluating the activity of daily life. It is self-administered on an interview basis. Figure B.1 shows a copy of the questionnaire.

The participant is asked to estimate the ease or difficulty of performing each activity when the activities are done without help, irrespective of the limb(s) the participant actually uses and whatever the strategies used to perform the activity. Note that the participant is never asked to perform the activities in front of the evaluator. The activities are presented in a random order to avoid any systematic effect. Ten different random orders of presentation are used. The evaluator selects the next one of the 10 orders for each new assessment, no matter which participant is tested. During the evaluation, the 3-level response scale is presented to the participant. The participant is asked to rate his/her perception on the response scale as "Impossible", "Difficult" or "Easy". The activities not attempted within the last 3 months are not scored and are entered as not applicable (check the question mark "?" on the scoring sheet). The activities that the participant does not perform because they are too difficult must be scored as "Impossible".

The responses to the questionnaire can be submitted for an online analysis on this website. The analysis uses the Rasch model to convert the raw scores into a linear measure. The linear measure can be determined even when some items have not been answered (missing responses will only reduce the precision of the measure). The online form is available with the items ordered in the 10 random orders used on the paper scoring sheets. Examiner selects the language and the order (1 to 10) that were used during the evaluation. Then enters the participant's responses into the online form and submits the form to display the evaluation report. The evaluation report is presented in Figure B.2.

The participant's manual ability (vertical red line) and its 95% confidence interval (dotted red lines) are located on the manual ability scale (abscissa), expressed in logits. The higher the ability of a participant the more the measure will be located to the right.

The logit is a linear unit that expresses the odds of success of the participant on any given item. The manual ability scale is centred on the average item difficulty (0 logit).

The item map lists the items from top to bottom in decreasing difficulty order. The item map shows the most probable score (0 = "Impossible", 1 = "Difficult" or 2 = "Easy") to each item as a function of the participant's manual ability and the difficulty of the item. Note that "Hammering a nail" is the most difficult item as it requires the highest ability to be succeeded easily; "Washing one's hands" is the easiest. Note also that the most probable score for any given item increases with the participant's manual ability. The item map can be used for treatment planning and follow-up as it shows the item(s) that should be recovered first during the rehabilitation process (obviously, the easier ones).

The sigmoid curve shown at the bottom relates the total score on the questionnaire to the manual ability measure (for a complete response set). Note that the score always increases with the manual ability, although, given the shape of the curve, the increase is not linear. Therefore changes of manual ability must be interpreted in linear logit units rather than in raw scores.

The participant's response to each item is circled (missing responses are not shown). In this particular case, the participant can still recover performance in most of the difficult items down to "Pulling up the zipper of trousers". The participant should first recover easier activities like "Pulling up the zipper of trousers" up to more difficult activities like "Hammering a nail".

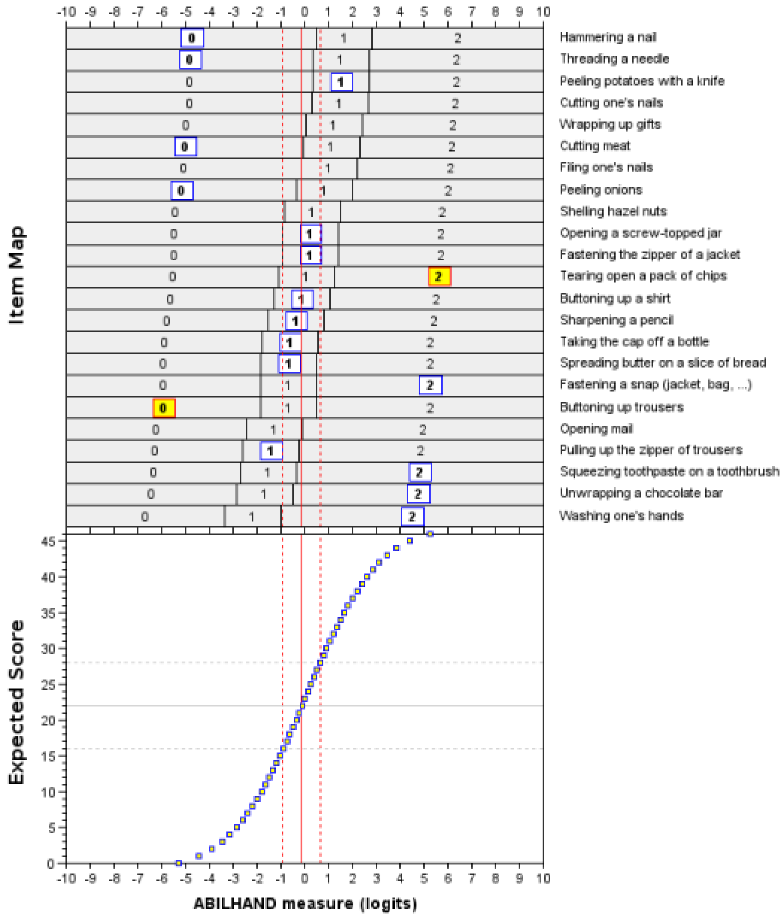
For any particular item, the range overlapping the 95% confidence interval indicates the most probable score(s) given the overall manual ability measure. Note that in the example (Figure B.2.), most scores fit with the overall manual ability measure of the participant indicating the participant scores are coherent across items. The item "Buttoning up trousers" is scored as "Impossible" while it is expected to be easier, given the overall manual ability measure. The item "Tearing open a pack of chips" is scored as "Easy" while it is expected to be more difficult, given the overall manual ability measure. These unexpected scores (circled in red on the report) may help you diagnose an atypical behaviour of the participant or other comorbidities.

The evaluation report also includes the numeric values for the participant's manual ability measure on the scale and the standard error of measurement (in logits), to keep those in records to measure the participant recovery at a future occasion.

	How **DIFFICULT** are the following activities?	**Impossible**	**Difficult**	**Easy**	**?**
1.	Pulling up the zipper of trousers				
2.	Peeling onions				
3.	Sharpening a pencil				
4.	Taking the cap off a bottle				
5.	Filing one's nails				
6.	Peeling potatoes with a knife				
7.	Buttoning up trousers				
8.	Opening a screw-topped jar				
9.	Cutting one's nails				
10.	Tearing open a pack of chips				
11.	Unwrapping a chocolate bar				
12.	Hammering a nail				
13.	Spreading butter on a slice of bread				
14.	Washing one's hands				
15.	Buttoning up a shirt				
16.	Threading a needle				
17.	Cutting meat				
18.	Wrapping up gifts				
19.	Fastening the zipper of a jacket				
20.	Fastening a snap (jacket, bag, ...)				
21.	Shelling hazel nuts				
22.	Opening mail				
23.	Squeezing toothpaste on a toothbrush				

Figure B.1. Empty copy of Abilhand questionary in English

ABILHAND evaluation report - rehab-scales.org



Item scores:

- 0 = Impossible
- 1 = Difficult
- 2 = Easy

Patient evaluation results:

- Patient score: 18 (18 items scored out of 23)
- Missing responses: 5
- Patient measure: -0.155 logits
- Standard Error: 0.405 logits

This evaluation report has been established according to:

- Test: ABILHAND, version 1.0
- Calibration: Chronic stroke patients, version 1.0
- Language: English
- Order: 1

Figure B.2. Example of an Abilhand evaluation report

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Summary

Simultaneous execution of cognitive and sensorimotor tasks is critical in daily life. The clinical usefulness of assessing the performance of a grip-lift task to evaluate motor function in healthy and neurological participants is largely recognised. However, these assessments are always performed in isolation. Here, we use a dual-task paradigm to examine whether dexterous manipulation, a highly habitual and seemingly automatic behaviour, involves high-order cognitive functions, in healthy adults and chronic stroke participants.

In dual-tasks, both healthy adults and chronic stroke participants significantly lengthen the initial phase of the movement and strengthen their grip throughout the grip-lift task. The differences were scaled to the needs in cognitive resources. Preload phase and grip forces were significantly increased in both hands of chronic stroke participants, with the strongest increase at the affected hand. However, the cognitive tasks did not appear to exert a stronger effect on motor performance. Cognitive task specifically recruiting working memory interacts with the planning and the on-line control of the fine grip manipulation. Thus dexterous manipulation is not a full automatic behaviour and depends on high-level cognition at some specific moment of its sequence. Assessing motor performance under cognitive load might be a more sensitive way to actually assess motor abilities and their impacts in real life situations.

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Erwan Guillery was born in Quimper (Brittany, France) in 1984. Since 2010, he holds a master of *sciences de la motricité, orientation générale à finalité spécialisée en thérapie manuelle et kinésithérapie du sport* from the Université catholique de Louvain (UCL). His first master thesis was devoted to the Neuronal correlates of visually guided movements in peripheral vision, with transcranial magnetic stimulation, and his second was devoted to the Analysis of long-term autocorrelations of the elderly walking at different speeds on a treadmill. Then he started a Ph.D. project in the Institute of Neuroscience (IoNS, UCL), under the co-supervision of Pr. Jean-Louis Thonnard and Pr. André Mouraux. His major interests focus on evaluating cognitive-motor interaction in dexterous movements under the constraint of cognitive loads.

Nous réalisons simultanément des tâches cognitives et motrices en permanence. Cependant, leurs évaluations sont toujours effectuées de manière isolée. Afin d'évaluer si la préhension fine implique des fonctions cognitives de haut niveau, nous avons recruté des participants sains et d'autres ayant subi un AVC au stade chronique. Les tâches cognitives ont affecté la planification et le contrôle en ligne de la préhension fine proportionnellement aux besoins en ressources cognitives des différentes doubles-tâches. La préhension fine n'est donc pas un processus purement automatique. Elle requiert des fonctions cognitives de haut niveau à certains moments spécifiques de son déroulement.
L'évaluation des interactions entre des tâches cognitives et motrices est un moyen plus sensible pour évaluer les activités dans un contexte plus proche de la vie de tous les jours.

Simultaneous execution of cognitive and sensorimotor tasks is critical in daily life. However, their assessments are always performed in isolation. We use a dual-task paradigm to examine whether dexterous manipulation, a highly habitual and seemingly automatic behaviour, involves high-order cognitive functions, in healthy adults and chronic stroke participants.
Cognitive tasks interact with the planning and the on-line control of the fine grip manipulation. The differences were scaled to the needs in cognitive resources. Thus dexterous manipulation is not a full automatic behaviour and depends on high-level cognition at some specific moment of its sequence. Assessing motor performance under cognitive load might be a more sensitive way to assess motor abilities in real life situations.