UNIVERSITEIT GENT
Faculteit Psychologie en Pedagogische Wetenschappen

Functional Unity and Diversity within Executive Control: A Study by means of Parametrical Variations of Executive Involvement in Reaction Time Tasks

Arnaud Szmalec

Promotor: Prof. Dr. André Vandierendonck

Proefschrift ingediend tot het behalen van de academische graad
van Doctor in de Psychologische Wetenschappen

2005

UNIVERSITEIT
GENT

Faculteit Psychologie en
Pedagogische Wetenschappen

Functional Unity and Diversity within Executive Control: A Study by means of Parametrical Variations of Executive Involvement in Reaction Time Tasks

Arnaud Szmalec

Promotor: Prof. Dr. André Vandierendonck

Proefschrift ingediend tot het behalen van de academische graad
van Doctor in de Psychologische Wetenschappen

2005

CONTENTS

ACKNOWLEDGEMENTS

This doctoral dissertation was accomplished while I was working as a fellow of the Special Research Fund at Ghent University. I thank aforementioned institution for the support.

The first person I would like to thank is Prof. Dr. André Vandierendonck, the promoter of this thesis. I thank him for introducing me to the domain of cognitive science and for the trust he put in me. He convinced me that experimental research is a valuable method to advance cognitive science. I believe that his role in the development of the Department of Experimental Psychology at Ghent University as it stands today, can not be overvalued. His continuous support throughout this project was greatly appreciated. I also thank the members of the supervisory committee for my PhD project: Prof. Dr. Wim Fias, Prof. Dr. Luc Crevits from the Department of Neurology and Dr. Bernie Caessens.

Second, I would like to thank my ever caring mother for her true and unconditional support over the years. Special thanks go to my father. My father grew up as an underprivileged and motherless child of WW II Polish refugees. I have a healthy respect and admiration for the way he still succeeded in life and I thank him and my mother for offering me the ideal circumstances to realize my ambitions.

Third, I would like to thank my partner, Sofie. She is the reason why - and I say this in all sincerity – I consider myself as leading the dream of a family life. Special thanks go to my daughter, Elle, for respecting her date of birth, which should be early March 2005, right after the birth of my academic baby. I am happy to see that she has adopted her father's punctuality…

Many thanks go to a true and long time friend (and colleague), Wouter Duyck. I admire him as a very rich personality and an excellent researcher.

Thanks to three great friend-colleagues who have played a significant role during the last four years. Timothy Desmet for the innumerable political discussions we pursued. I am pleased and proud to see that we have solved nearly all world's biggest issues by now, from East Timor, over the Middle-East, to Chiapas. My former conference-mate Stijn De Rammelaere, who is now supplying excellent 'pioneering work' to the nonacademic world. A marvel of artificial intelligence, the first successful prototype cyborg called Wouter De Baene, who we adopted as a good friend but who left our department for some monkey business… Thank you also to Baptist Liefooghe and Frederick Verbruggen for the excellent research-related discussions and for putting up with me in the same office.

My final thoughts go to my grandparents on mother's side who passed away during the course of my PhD work.

Arnaud Szmalec

Ghent, February 2005

CHAPTER 1

EXECUTIVE CONTROL: AN OVERVIEW

When asked to define the concept of executive control, any researcher in the field will agree that it is much easier to explain what it is not, than to say what it exactly is. In this first chapter, I will nevertheless try to provide the reader with an introduction to the concept of executive control and with a résumé of the unsatisfactory state of affairs in executive function theory today. The introduction ends with the presentation of the research issues addressed in the present dissertation.

INTRODUCTION

Animals with less than a hundred thousand brain cells are able to collect food, avoid predators and raise offspring. The human brain holds approximately 100 billion nerve cells. The interaction between the large amounts of neurons offers much flexibility to human behavior. However, increasing flexibility induces more complexity in the sense that within a diversity of behavioral options, the appropriate one has to be selected as a function of a specific goal. An emergent property of this behavioral diversity is that somewhere in the brain must reside a supervisory, coordinative cognitive function which guarantees that appropriate action is taken so that purposeful, goal-directed behavior arises. In cognitive psychology, this notion of a supervisory cognitive function is mostly referred to by the term *executive control* or *executive functioning*.

The assumption of a distinction between a *control* mechanism and a set of *controlled* mechanisms (such as language or memory) is not an arbitrary one. The roots of executive function research lay in neuropsychology and it is particularly from this domain that the need for a functional and anatomical distinction between control and controlled mechanisms stems (e.g. Shallice & Burgess, 1991). Over the years, many cases have been described of patients suffering from an impairment of executive control functions, which is generally referred to as *dysexecutive* or frontal lobe syndrome (Duncan, 1986; Luria, 1969; Shallice, 1982; Shallice & Burgess, 1991, 1993, 1996). Dysexecutive patients "…show a broad loosening in the structure of thought and action: the normal picture, a coherent sequence of actions and mental activities that allow the achievement of some selected goal, is distorted, sometimes bizarrely, by the omission of crucial components and by the intrusion of irrelevant or interfering material. According to the circumstances, the patient might seem mentally passive or inert, or disinhibited and distracted…" (Duncan, 2001, p. 820). What is particularly interesting about this syndrome, is that dysexecutive symptoms such as disinhibition, mental rigidity, perseverance or inertia can co-occur with intact language, short-, or long-term memory functioning, for example. This indicates that the syndrome does not affect the cognitive system as a whole but that it selectively impairs the mechanism(s) responsible for producing effective, organized and purposeful behavior. More broadly speaking, it is not the entire repertoire of cognitive abilities that is affected in this kind of pathology, but the cognitive system that coordinates these abilities for the purpose of daily goal-directed behavior. This pattern of selective impairment of executive functioning has lead towards the consensus that control and controlled processes can be functionally differentiated (Baddeley & Wilson, 1988). As can be derived from the term "frontal lobe syndrome", executive control and the set of controlled cognitive abilities can also be distinguished on neuroanatomical grounds. Based on the observation that frontal lesions are strongly correlated with executive impairment, executive control is since long assumed to be a privileged function of the frontal lobe, more precisely of the *prefrontal cortex* (Shallice, 1982, 1988).

AUTOMATIC VERSUS CONTROLLED BEHAVIOR

In the previous section, it was described how in cognitive science a distinction is made between controlled and control processes, both on functional and on anatomical grounds. Of course, not all human cognitive activity is executed under executive control. Behavior can also be the outcome of automatic processing (Atkinson & Shiffrin, 1968; Schneider & Shiffrin, 1977). The distinction between automatic and controlled behavior (see also Schneider, 1993) is important in order to fully understand the concept of executive control. *Automatic* behavior, such as automatically orienting to an unexpected event, primarily relies on bottom-up processing which means that the behavior is largely dependent on physical properties of the event (e.g. the loudness of a sound or the size of a visual stimulus). Moreover, automatic behavior is suitable for routine activities but quite inflexible and inefficient in novel or problematic situations. *Controlled* behavior on the other hand, heavily relies on top-down processing, which signifies that the behavior is guided by an intention or goal. Controlled processing is much more flexible and crucial to manage novel, dangerous or problematic situations (Norman & Shallice, 1986).

Behavior is highly *adaptive* and in this view, also automatic and controlled behaviors do not stand for two discrete categories of cognitive abilities (Miller, 1999). First, controlled behavior can become more automated. Second, certain circumstances might require perfectly automated behavior to become executively controlled again. Consider the following example. When a mainland European child is introduced to road traffic, it is instructed always to look to the left before crossing a street. At the beginning, it imposes heavy demands on the child's executive control system to apply these rules. By contrast, an adult person is able to cross the street while even pursuing an in-depth conversation, because the crossing rule is applied automatically by that age. This illustrates how controlled behavior can become more automated. However, when a mainland European adult travels to the UK, crossing the street becomes problematic because the inverse traffic rules apply there and as a consequence, the automated behavior becomes ineffective, even dangerous. Accordingly, crossing the street in the UK will again impose large demands on a mainland European person's executive control system in order to suppress the automated behavior and apply the unfamiliar UK rule. This shows that specific behavior (like crossing the street) can be either controlled or automated, depending on the specific circumstances.

The distinction between automatic and controlled behavior might be quite understandable, still very little is known about the cognitive processes that guide controlled behavior (Rabbitt, 1997). Executive processing has always been and still is one of the least understood aspects of human cognition. Researchers have spoken about a “Cinderella area of (cognitive) neuropsychology” (Burgess, 1997, p. 81) and an “embarrassing zone of almost total ignorance” (Monsell, 1996, p. 93). One main reason for the slow and limited progress in executive function research is that it has proven particularly difficult to obtain good measures of executive performance (Burgess, 1997), when compared to other domains of cognitive science like word recognition, sentence processing or mental arithmetic, for example. A number of methodological issues encountered in executive function research are addressed in the following section.

MEASURING EXECUTIVE FUNCTIONING

Any study that attempts to gain an insight into the cognitive processes underlying executive control requires a valid and reliable *executive measuring instrument* or task. But what determines the executive nature of a task? There are at least three approaches to define an executive task. One approach is to use patients with frontal lobe damage as the gold standard, and call tasks on which these patients are impaired executive tasks, based on the assumption that the executive control mechanisms reside in the frontal lobes. Another approach considers correlation with Spearman's (1927) *g*F (fluid intelligence) as the standard for determining executive involvement (Duncan, 1995), despite the fact that differences in intelligence are within the same approach often accounted for by differences in executive ability. The third approach is to define a certain function as executive, and to call executive any task that is assumed to involve this function. The problem with those three definitions is that they all suffer from circularity and that there exists no straightforward way to break through it. Although the distinction between circularity and convergence is sometimes debatable, converging evidence from three approaches that tackle the same underlying mechanism is the only way to advance in executive function research.

One important psychometric issue in the measurement of executive functioning is the *task purity* problem (Rabbitt 1997). It is particularly difficult to obtain relatively pure measures of executive control. On the one hand, many classical executive tasks (e.g. Wisconsin Card Sorting Test, Tower of London and Tower of Hanoi) are not pure in that they tap both executive and non-executive functions, such that performance can be disrupted in many, also non-executive ways (Reitan & Wolfson, 1994). This can explain why executive tasks generally have poor *discriminant* validity (i.e. discriminating between executive and non-executive abilities). Also the *construct* validity of many conventional executive tasks is low. Several studies have examined the intercorrelations of performance on batteries of executive tasks and generally the correlations are low with no substantial clustering (Duncan, Johnson, Swales, & Freer, 1997; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000; Rabbitt, 1997). This is the case even between executive tasks that are assumed to measure one specific postulated executive function, such as inhibition (e.g. Friedman & Miyake, 2004). This indicates that the conventional executive tasks often appear to have little more in common than what executive and non-executive tasks have in common, and this is particularly worrying for measures that are intended to tap the same theoretical construct. Finally, also the *test-retest reliability* of executive tasks is generally poor. Several studies pointed out that especially novel tasks are effective in assessing executive functioning (see Rabbitt, 1997), but because tasks are novel only once, the test-retest reliability is low, a concern that seems to be largely applicable to executive tasks.

So far, I have introduced the concept of executive control, and outlined the unsatisfactory state of affairs in executive function research today (for an elaborate review, the reader is referred to Rabbitt, 1997). The purpose of the present dissertation is to contribute to a clarification of the concept of executive control from a working memory perspective. The following section explains why working memory is believed to play a central role in executive control and how Baddeley's (1986) working memory model was used as a theoretical framework for the behavioral studies reported in this dissertation.

WORKING MEMORY AND EXECUTIVE CONTROL

The essence of executively controlled behavior is that it is not random or arbitrary, but that it serves an *internal goal*. The notion of goal-directed behavior is central to any theory of executive functioning (Miller & Cohen, 2001). Meaningful, purposeful behavior can only be established when a task-goal and the means to achieve this goal (i.e. the task-rules) are efficiently represented. Analogously, the failure to maintain a task goal is central to the concept of dysexecutive behavior. An increasing number of studies argue that *goal neglect*, the disregard of a task requirement although it has been understood (Duncan, 1995), is to an important degree responsible for the poor performance on executive tasks, as observed in patient populations with frontal lobe damage (Nieuwenhuis, Broerse, Nielen, & de Jong, 2004).

Assuming that the effectiveness of controlled behavior is associated with the capacity to maintain task-goals and task-rules active, then somewhere in the brain a mechanism must reside that serves this maintenance function. The cognitive mechanism par excellence responsible for temporarily keeping information in an active state, is working memory. It thus seems reasonable to assume that task-goals and task-rules are types of information that can be maintained in working memory, through which working memory is attributed a central role in executive functioning. Traditionally, working memory is defined as a system for short-term maintenance and manipulation of information and in this view, most working memory theories distinguish between storage and processing (see Miyake & Shah, 1999, for a comprehensive review of contemporary models of working memory). One of the most influential working memory models of the last decades is Baddeley's model (Baddeley & Hitch, 1974; Baddeley, 1986). Baddeley's working memory model was originally conceived as a tripartite system, comprising an attentional control system, the *Central Executive*, which coordinates the operation of two subsidiary systems, the *Phonological Loop* and the *Visuospatial Sketch Pad*. The Phonological Loop is held responsible for the temporary storage of speech-based, verbal material (Baddeley, 1986) whereas the Visuospatial Sketch Pad is assumed to preserve imagery and spatial information (Logie, 1995).

Baddeley's model was used as a theoretical framework for the working memory studies reported in this dissertation, for a number of reasons. First, as a multicomponent model, it is relatively exhaustive in the sense that it encompasses both the concept of executive control and two specialized, domain-specific storage systems, through which a substantial part of working memory is theoretically covered. This *theoretical advantage* is of particular importance for a research project as the current one, which is aimed to differentiate executive from non-executive processes in working memory. The second is a *methodological reason*. Within Baddeley's model, there is a long history of studies that have used the dual-task paradigm to investigate working memory involvement in a variety of cognitive abilities, both in healthy and pathologic, young and older populations (e.g. Baddeley, Bressi, Dellasala, Logie, Spinnler, 1991; Baddeley, Gathercole, & Papagno, 1998; Bradley, Welch, & Dick, 1989; Duyck, Szmalec, Kemps, & Vandierendonck, 2003; Gathercole, 1999; Kemps, Szmalec, Vandierendonck, & Crevits, in press). In the dual-task paradigm, a target task is performed concurrently with a secondary task thought to tap a specific working memory component. If both tasks substantially interfere, it is concluded that the specific working memory component is involved in the target task and thus in the cognitive processing that the task is assumed to measure. For these kinds of designs, the term "dual-task paradigm" is becoming less usual than the more appropriate term "*selective interference paradigm*". Both names imply that tasks are implemented in a so-called dual-task setting but it is particularly the notion of selectively interfering with a specific working memory component or component process that makes the methodology valuable.

Baddeley's working memory model has benefited from decades of experimentation. Especially the theory on verbal and visuospatial working memory received much attention. These theoretical constructs are nowadays empirically well-founded, easy to operationalize and they can account for a majority of empirical findings from diverse populations. On the other hand, the development of the Central Executive, working memory's[1] theoretical implementation of the concept of executive control, has been much slower and problematic (Baddeley, 1996). However, the difficult advance in executive function research is not especially characteristic of the working memory model; it is rather exemplary of an unsatisfactory situation in all of executive function research. Nevertheless, if Baddeley's working memory model intends to remain influential in the future, its theory on executive functioning (the Central Executive) needs more elaboration. To this day, promising steps have been taken in that direction (Baddeley, 1996; Miyake et al., 2000; Rabbitt, 1997) but still a lot needs to be done. In what follows, I will explain how the present dissertation aims to contribute to reach that

---

[1] Note that from this point on, the term working memory will be used throughout the text, without explicitly mentioning that Baddeley's model is referred to.

objective, but first, the working memory theory on executive control, for which the Central Executive stands, will be outlined briefly.

THE CENTRAL EXECUTIVE

Although conceptualized already with the inception of the model in 1974, a more clear definition of the Central Executive (CE) had to wait until 1986, when Baddeley equated the Central Executive with the Supervisory Activating System (SAS) component of Norman and Shallice’s (1980) model of attentional control. Initially, executive functioning was associated with rather vague concepts such as planning or problem solving and the role of the CE in those cognitive abilities was equally ill-defined. An often heard criticism at that time was that the CE is nothing more than a homunculus, a little man who sits in the brain and in some mysterious way makes all the important decisions (Baddeley, 1996). For an important part under pressure of the methodological and psychometric restraints described earlier, executive abilities like planning or problem solving have been redefined in a set of executive functions, such as inhibition, updating or switching (e.g. Miyake et al., 2000). Also complex problem solving tasks (such as the Tower of London) have become less conventional measures of executive control, now that they have given way to executive tasks that are much more specific in the executive function(s) they target (e.g. Go/Nogo task for inhibition, *n*-back task for updating and Trail Making Test for switching). Also the definition of the CE has been updated (Baddeley, 1996) and concepts as inhibition, switching and dual-tasking, for instance, are now generally seen as functions of the CE.

In the light of this evolution, two theoretical issues have become particularly pertinent. They are both related to the following question: Is executive control a *unitary system* with multiple functions or is it best regarded as an agglomeration of *functionally separable* control processes that can interact? The first problem is to identify the potentially separable control processes.

Although often postulated executive functions such as inhibition or updating are more basic than concepts like planning or decision-making, it is possible that they are not *the* basic elements of executive control and that they are in turn fractionable into more fundamental units of executive control. The *fractionability of the Central Executive* is an important topic in working memory research today (Baddeley, 1996; 2000). Second, how are these control processes or the often postulated executive functions related to each other? Are they indeed functionally differentiable and is the Central Executive merely a generic term for a number of separable executive control functions, or is it equally reasonable to assume that the often postulated executive functions reflect different task demands that are met by a common, unitary control system (e.g. Miyake et al., 2000)? In summary, the main challenge for executive function researchers today is to find out (1) to what extent executive functions can be fractionated (i.e. which are the basic elements of executive control) and (2) what we are essentially fractionating: executive control processes or executive tasks/task demands (i.e. executive mechanisms versus task demands that require executive resources)?

A number of - mainly correlational - studies have started to address the issues outlined above. Lehto (1996), for example, was among the first to observe low intercorrelations between commonly used executive function tests (Wisconsin Card Sorting Test, Goals Search Task, Tower of Hanoi). Similarly, Miyake et al. (2000) examined the intercorrelations between a set of tasks that are assumed to measure the executive functions inhibition, updating and shifting. The results of the latter study pointed towards moderate intercorrelations, but also clear separability. The patterns of correlation observed by Lehto and Miyake are mostly used as empirical evidence against the hypothesis that executive control is a unitary system. However, this is somewhat at odds with the studies that find similar patterns of moderate correlation between performance on tasks that are assumed to measure the same executive function, like inhibition for example (e.g. Duncan et al., 1997; Friedman & Miyake, 2004). The latter finding is in turn often taken as evidence that also concepts as inhibition are not unitary. This may perfectly be true, but if studies show low patterns of correlation between any kind of executive task, one should also be sensitive to the alternative explanation that the correlations might be masked by psychometric problems (e.g. task impurity), as described earlier in this introduction. If the conventional executive tasks are not pure because they involve both executive and non-executive processes, moderate correlations amongst those tasks can still point towards a common underlying executive control mechanism.

A number of years ago the original working memory model, as described above, has been revised. Baddeley (2000) argued that working memory contains a temporary storage system for multimodal information which makes it possible to link short-term memory with long-term memory information in a unitary episodic representation. One of the main reasons for putting forward a multimodal storage system was that the Central Executive itself was conceived of as a control system with no storage capacity and that a number of empirical findings could not be accounted for without such capacity (e.g. Baddeley, Vallar, & Wilson, 1987; Wilson & Baddeley, 1988). Consequently, a fourth component was added to the working memory model, called the *Episodic Buffer*. To this day, the Episodic Buffer remains principally a theoretical concept that is not made operational yet. It is thus not possible yet to directly investigate its role in executive control, from a working memory perspective. However, assuming that working memory would be involved in executive control by maintaining the task goal and the means to achieve that goal, and given that the Episodic Buffer has a modality-free maintenance capacity while the Central Executive has not, the Episodic Buffer may eventually turn out to play a role in executive control.

THE PRESENT DISSERTATION

From what preceded, it can be understood that the concept of executive control is, although essential for purposive behavior, still poorly understood.

What is needed in order to improve the situation is a number of good paradigms to study executive control. Today, there is a lack of such paradigms (Barnard, Scott, & May, 2001; Van der Linden, Collette, Salmon, Delfiore, Degueldre, Luxen et al., 1999). The purpose of the current dissertation is twofold. First, it is aimed to meet this methodological shortcoming by working out a new method to investigate executive control within the working memory framework. The second objective is to apply the new method in order to gain a theoretical insight into the concept of executive control, by way of addressing the following research question: is executive control a unitary system or is it rather a conglomerate of separable executive functions? The goal of the thesis is pursued with both behavioral and electrophysiological studies.

RATIONALE

The rationale of the new method is based on earlier working memory studies which were aimed at developing relatively simple secondary tasks for selectively interfering with the Central Executive (e.g. Vandierendonck, De Vooght, & Van der Goten, 1998a; 1998b). At that time, while the selective interference paradigm (cfr. supra) was frequently used to investigate working memory involvement in several cognitive abilities or tasks, there already existed a number of secondary tasks that selectively interfered with the working memory slave systems (e.g. articulatory suppression for the Phonological Loop and matrix tapping for the Visuospatial Sketchpad). However, it proved much more difficult to obtain relatively pure executive secondary tasks; pure in the sense that the tasks interfere with the Central Executive with no measurable involvement of the slave systems. In answer to these difficulties, Vandierendonck and colleagues (1998a) presented the Random Interval Repetition (RIR) task as a selective source of interference with executive control in working memory (see also Random Interval Generation task in Vandierendonck et al., 1998b). In essence, the RIR task is a parametrical variation on a simple RT task in the sense that the Inter-

Stimulus Intervals (ISIs) are not fixed but random. By comparing the patterns of dual-task interference of the RIR task, relative to the dual-task effects of a Fixed Interval Repetition task (FIR task or standard simple RT task with fixed ISI) on a number of primary tasks involving executive control, Vandierendonck et al. (1998a) demonstrated that the randomness of the ISIs is a determining factor for executive involvement in the RIR task.

The rationale behind the current strategy is that knowledge of the *task manipulations or parameterizations* that affect the executive demands of a task also contains information about the executive nature of the process(es) that underlie performance on that task. With respect to the randomization parameter for example, it can be postulated that input monitoring is required when stimuli are presented at an unpredictable (or random) rate. In this view, the observation that a random simple RT task involves more executive control than a fixed simple RT task implies that input monitoring is an executive process. Accordingly, the methodological goal of this dissertation is to establish a method for estimating the executive demands associated with parametrical variations on reaction time tasks (by analogy with the random versus fixed simple RT task comparison) in order to gain knowledge of the task demands and the respective process(es) that constitute executive control.

BEHAVIORAL STUDIES

In Chapters 2 and 3, I present two behavioral studies in which the new method is introduced, validated and further applied. Chapter 2 operationalizes the process of response selection ─ which was quite recently proposed to involve executive control (e.g. Hegarty, Shah, & Miyake, 2000) ─ by comparing a simple RT task and a choice RT task (a choice RT task involves response selection in addition to the processing demands of the simple RT task; Schubert, 1999). Then, in a series of experiments, the executive demands of response selection are estimated by testing whether the specified task manipulation (simple RT task versus choice RT task) causes additional interference with primary tasks that involve executive control and by verifying whether the additional interference is not mediated at the level of working memory's slave systems. In Chapter 3, a similar approach is taken. Starting from the hypothesis that a one-back choice RT task (i.e. an RT task that requires participants to delay a response until presentation of the next stimulus) operationalizes the executive function of updating, we investigate the patterns of dual-task impairment of a choice RT task and a one-back choice RT task on a number of primary tasks that tap the different subcomponents of working memory.

ELECTROPHYSIOLOGICAL STUDIES

As denoted before, the method to study executive control introduced in the work at hand is intended to gain knowledge of the task demands and the respective process(es) that constitute executive control. Unfortunately, task demands and the processes that deal with those demands do not necessarily form a one-to-one mapping (Burgess, 1997) and this makes it particularly difficult in the behavioral studies to draw conclusions at the processing level. In Chapter 3, for example, we compare the patterns of dual-task interference of a standard choice RT task with a one-back choice RT task. On theoretical grounds, it can be argued that the one-back choice RT task operationalizes the postulated executive process of updating (cfr. Chapter 3) and that therefore, the one-back task is anticipated to involve more executive control than a standard choice RT task. Suppose that this hypothesis turns out to be correct, what can we conclude about the process of updating? It would be quite circular to interpret such a result as evidence for the position that updating is an executive process. As I argued earlier in this introduction, a good way to get round circularity is to search for convergence in other paradigms. In this vein, Chapters 4 and 5 estimate the effects of the parametrical RT task manipulations on neurophysiological processes by means of Event Related brain Potentials (ERPs). Scalp-recorded ERPs are generally accepted as a valuable method for indexing brain activity underlying cognitive processes. In addition, ERP components associated with RT tasks have been well validated throughout decades of research. Accordingly, the purpose of the electrophysiological part of this dissertation is to explore the ERP basis of the effects observed in the behavioral studies. By doing this, I hope to gain an insight into the cognitive processes underlying executive task performance.

REFERENCES

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence (Ed.), *The psychology of learning and motivation*. New York: Academic Press.

Baddeley, A. D. (1986). *Working Memory*. Oxford: Oxford University Press, Clarendon Press.

Baddeley, A. D. (1996). Exploring the Central Executive. *Quarterly Journal of Experimental Psychology, 49A*, 5-28.

Baddeley, A.D. (2000). The Episodic Buffer: A new component of Working Memory? *Trends in Cognitive Sciences, 4,* 417-423.

Baddeley, A.D., & Hitch, G. (1974). Working Memory. In G. A. Bower (Ed.), *Recent Advances in Learning and Motivation*. (pp. 47-90). New York: Academic Press.

Baddeley, A.D., & Wilson, B.A. (1988). Frontal amnesia and the dysexecutive syndrome. *Brain & Cognition, 7,* 212-230.

Baddeley, A.D., Gathercole, S.E. & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105*, 158-173.

Baddeley, A.D., Vallar, G. & Wilson, B. A. (1987). Sentence comprehension and phonological memory: some neuropsychological evidence. In: Coltheart, M. (ed.). *Attention and Performance XII: The Psychology of Reading.* (pp. 509-529). Lawrence Erlbaum Associates, Hove and London (UK); Hillsdale, N.J. (USA).

Baddeley, A.D., Bressi, S., Della Sala, S., Logie, R., & Spinnler, H. (1991). The decline of working memory in Alzheimer's disease: a longitudinal study. *Brain, 114*, 2521-42.

Barnard, P. J., Scott, S. K., & May, J. (2001). When the Central Executive lets us down: Schemas, attention, and load in a generative working memory task. *Memory, 9,* 209-221.

Bradley, V.A., Welch, J.L., & Dick, D.J. (1989). Visuospatial working memory in Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry, 52*, 1228-1235.

Burgess, P.W. (1997).Theory and methodology in executive function research. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 81-116). Hove, UK: Psychology Press.

Duncan, J. (1986). Disorganisation of behavior after frontal lobe damage. *Cognitive Neuropsychology, 3,* 271-290.

Duncan, J. (1995). Attention, intelligence and the frontal lobes. In M.S. Gazzaniga (Ed.), *The Cognitive Neurosciences* (pp. 721-733). Cambridge, MA: MIT Press.

Duncan, J. (2001). An adaptive coding model of neural function in prefrontal cortex. *Nature Reviews Neuroscience, 2*, 820-829.

Duncan, J., Johnson, R., Swales, M., & Freer, C. (1997). Frontal lobe deficits after head injury: Unity and Diversity of function. *Cognitive Neuropsychology, 14,* 713-741.

Duyck, W., Szmalec, A., Kemps, E., & Vandierendonck, A. (2003). Verbal working memory is involved in associative word learning unless visual codes are available. *Journal of Memory and Language, 48*, 527-541.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent variable analysis. *Journal of Experimental Psychology: General, 133*, 101-135.

Gathercole, S. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Science, 3*, 410-418.

Hegarty, M., Shah, P., & Miyake, A. (2000). Constraints on using the dual-task methodology to specify the degree of central executive involvement in cognitive tasks. *Memory & Cognition, 28*, 376-385.

Kemps, E., Szmalec, A., Vandierendonck, A., & Crevits, L. (in press). Visuo-spatial processing in Parkinson's disease: Evidence for diminished visuo-spatial sketch pad and central executive resources. *Parkinsonism and Related Disorders.*

Lehto, J. (1996). Are executive functioning tests dependent upon Working Memory capacity? *Quarterly Journal of Experimental Psychology, 49A*, 29-51.

Logie, R. H. (1995). *Visuo-spatial working memory*. Hillsdale: Erlbaum.

Miller, E.K. (1999). Straight from the top (News and Views). *Nature, 401,* 650-651.

Miller, E.K. & Cohen, J.D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167-202.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49-100.

Miyake, A., & Shah, P. (Eds.). (1999). Models of working memory: Mechanisms of active maintenance and executive control. New York: Cambridge University Press.

Monsell, S. (1996). Control of mental processes. In V. Bruce (Ed.), *Unsolved mysteries of the mind* (pp. 93-148). Hove: Erlbaum.

Nieuwenhuis, S., Broerse, A., Nielen, M.M.A., & De Jong, R. (2004). A goal activation approach to the study of executive function: An application to antisaccade tasks. *Brain and Cognition, 56*, 198-214.

Norman, D.A. & Shallice, T. (1980). Attention to action: Willed and automatic control of behavior. Center for Human Information Processing (Technical report No. 99). (Reprinted in revised form in R.J. Davidson, G.E. Schwartz, & D. Shapiro [Eds] [1986], *Consciousness and self regulation*. New York: Plenum Press.)

Norman, D.A. & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R.J. Davidson, G.E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation*. New York: Plenum Press.

Rabbitt, P. (1997). *Methodology of frontal and executive function*. Hove, UK: Psychology Press.

Reitan, R.M., & Wolfson, D. (1994). A selective and critical review of neuropsychological deficits and the frontal lobes. *Neuropsychology Review, 4,* 161-198.

Schneider, W. (1993). Varieties of working memory as seen in biology and in connectionist control architectures. *Memory & Cognition, 21,* 184-192.

Schneider, W. & Shiffrin, R.M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review, 84*, 1-66.

Shallice, T. (1982). Secific impairments of planning. *Philosophical Transactions of the Royal Society B, 298,* 199-209.

Shallice, T. (1988). *From neuropsychology to mental structure.* New York: Cambridge University Press.

Shallice, T., & Burgess, P.W. (1991). Higher order cognitive impairments and frontal lobe lesions in man. In H.S. Levin, H.M. Eisenberg, & A.L. Benton (Eds.), *Frontal lobe function and dysfunction* (pp. 125-138). New York: Oxford University Press.

Shallice, T., & Burgess, P.W. (1993). Supervisory control of action and thought selection. In A. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, awareness and control. A tribute to Donald Broadbent* (pp. 171-187). Oxford: Clarendon press.

Shallice, T., & Burgess, P.W. (1996). The frontal lobes and the temporal organization of behavior. *Philosophical Transactions of the Royal Society of London B, 351,* 1405-1412.

Spearman, C. (1927). *The abilities of man.* New York: Macmillan.

Van der Linden, M., Collette, F., Salmon, E., Delfiore, G., Degueldre, C., Luxen, A., & Franck, G. (1999). The neural correlates of updating information in verbal working memory. *Memory, 7,* 549-560.

Vandierendonck, A., De Vooght, G., & Van Der Goten, K. (1998a). Interfering with the Central Executive by means of a Random Interval Repetition task. *Quarterly Journal of Experimental Psychology, 51A*, 197-218.

Vandierendonck, A., De Vooght, G., & Van Der Goten, K. (1998b). Does random time interval generation interfere with working memory executive functions? *European Journal of Cognitive Psychology, 10*, 413-442.

Wilson, B.A., & Baddeley, A.D. (1988). Semantic, episodic, and autobiographical memory in postmeningitis amnesic patients. *Brain and Cognition, 8,* 31-46.

CHAPTER 2
RESPONSE SELECTION INVOLVES EXECUTIVE CONTROL EVIDENCE FROM THE SELECTIVE INTERFERENCE PARADIGM

***Memory & Cognition* (in press)**[1]

The present study investigated whether response selection involves executive control, by using the selective interference paradigm within Baddeley's (1986) working memory framework. The interference due to response selection was estimated by comparing the patterns of dual-task interference of a simple and a choice RT task with a number of established working memory tasks. Experiment 1 compared the impairment of the RT tasks and articulatory suppression on forward and backward verbal serial recall. Experiment 2 measured the adverse effects of the RT tasks and matrix tapping on forward and backward visuospatial serial recall. Finally, Experiment 3 examined the impairment of the RT tasks on two measures of executive control, namely letter and category fluency. Altogether, the three experiments demonstrated that response selection interferes with executive control and that the interference is not produced at the level of working memory's slave systems, which supports the assumption of executive involvement in response selection.

---

[1] This paper was co-authored by André Vandierendonck and Eva Kemps

INTRODUCTION

The notion of an “executive” system refers to a domain-free, limited-capacity attentional mechanism that is responsible for the control and coordination of cognitive processes during complex cognitive tasks. For many years, executive control has been one of the least understood parts of human cognition. At the outset of executive function research, ill-defined concepts such as planning or problem-solving were used as references of executive control (see Rabbitt, 1997, for a review). Over the years, these higher-level concepts have been refined in a number of more basic executive functions, such as inhibition, switching or updating (e.g. Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). It is obvious that the tasks used to measure these functions call on an array of processes and that some - but probably not all - of these processes involve control of attention or executive control. Thus, underlying the traditionally proposed executive functions, more fundamental processes of executive control may be at work.

In recent years, a number of studies within various paradigms of cognitive psychology have suggested that executive control might be involved in response selection (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Hegarty, Shah, & Miyake, 2000; Klauer & Stegmaier, 1997; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000; Smyth & Scholey, 1994) or in a response selection task (i.e. a choice reaction time task; Allain, Carbonnell, Burle, Hasbroucq, & Vidal, 2004). Nevertheless, the idea that response selection is executively controlled remains somewhat controversial. One reason for the controversy might be that the term “executive” has always been associated with higher-order cognition, while response selection is instead believed to be a basic process. Another reason could be that the idea of an executively controlled response selection process is uninviting since virtually every cognitive task involves response selection. In this view, almost every cognitive task requires executive control to some extent. As a consequence, even the use of simple secondary tasks, such as spatial tapping and articulatory suppression, might become problematic if it would appear that at least under particular conditions, these tasks require an executively controlled response selection process (Hegarty et al., 2000). We suggest that this skepticism is largely a result of the rather loose usage of the term response selection. To avoid any such ambiguity, in the context of the present study, response selection is understood as “a decisional stage about the identity of a required reaction” (Schubert, 1999, p. 422). This definition imposes a restriction in the sense that not every produced response is the result of a deliberate choice process.

PRESENT STUDY

This study was set up in order to investigate whether executive control is involved in response selection. The experimental rationale is based on the selective interference paradigm, using Baddeley’s (1986) working memory (WM) model as a theoretical framework. The original WM model proposes that the architecture of working memory comprises two slave systems, one for short-term maintenance of phonological information (the Phonological Loop) and a similar one for visuospatial codes (the Visuospatial Sketchpad). These two storage systems are controlled and coordinated by a supervising agent, the Central Executive, which is assumed to be responsible for executive control.

In the present study, the interference due to response selection was estimated by comparing the patterns of dual-task interference of a simple and a choice RT task with a number of established working memory tasks. According to several authors, the difference between both RT tasks lies in the fact that the choice RT task involves response selection, in the sense of a decisional stage about the identity of a required response, whereas the simple RT task does not (Donders, 1868; Frith & Done, 1986; Schubert, 1999).

The hypothesis of the current investigation is that the requirement to select among responses calls on executive control, but does not require verbal or visuospatial processing. Accordingly, Experiment 1 used forward and backward verbal serial recall tasks in order to determine whether the interference due to a choice RT task is larger when the primary task requires more executive control and whether this interference is produced at the level of the Phonological Loop. Experiment 2 used forward and backward visuospatial serial recall tasks for a similar test at the level of the Visuospatial Sketch Pad. Finally, a traditional neuropsychological task, namely verbal fluency, was used in Experiment 3 to determine whether a choice RT task caused additional interference with executive control.

EXPERIMENT 1

The first experiment was designed to investigate whether the interference due to a choice RT task is larger when the primary task requires more executive control and whether this interference is produced at the level of the Phonological Loop. To that end, we compared forward and backward serial recall of consonants under single-task conditions and under three dual-task conditions in which forward and backward serial recall was simultaneously executed with the simple RT task, the choice RT task and with articulatory suppression (i.e. a task that selectively interferes with verbal processing).

In forward verbal serial recall, participants are asked to reproduce the verbal material in the same order of presentation whereas in backward recall, the verbal material is recalled in the reverse order of presentation. Performance for backward recall is usually observed to be worse compared to forward recall, although different measures of performance and manipulations of the nature of the verbal material have produced some exceptions (e.g. Engle, Tuholski, Laughlin, & Conway, 1999; Farrand & Jones, 1996). By cuing the required direction either pre or post presentation of the items, early studies (Hinrichs, 1968; Nilsson, Wright, & Murdock, 1979) have demonstrated that participants reverse verbal material at encoding and not at retrieval, provided that the direction of recall is known in advance. With respect to the nature of the cognitive processes involved in forward and backward verbal serial recall, there is a nowadays predominant view which Rosen and Engle (1997) called the Complexity view, which explains the differences between both directions of verbal recall in terms of processing complexity or executive demands. It states that both forward and backward recall of verbal items involve a similar degree of phonological processing (Rosen & Engle, 1997), and that - beside the executive demands associated with verbal serial recall in general (e.g. Engle et al., 1999) - backward recall requires a directional transformation which taxes additional executive resources compared to forward recall (Ashman & Das, 1980; Case & Globerson, 1974; Jensen & Figueroa, 1975; Schofield & Ashman, 1986). Over the years, several studies have supported the view that the reversing operation involved in backward verbal serial recall relies on executive control (Elliot, Smith, & McCulloch, 1997; Farrand & Jones, 1996; Gathercole, 1999; Gathercole & Pickering, 2000; Groeger, Field, & Hammond, 1999; Lezak, 1995; Smyth & Scholey, 1992; Vandierendonck, De Vooght, & Van der Goten, 1998a; 1998b).

The evidence for a comparable verbal involvement and a differential executive involvement in forward and backward verbal serial recall tasks offers a rationale to implement the latter tasks in a selective interference paradigm in order to dissociate verbal from executive involvement in an interference task. Given that participants perform the directional transformation at encoding when the direction of recall is pre-cued, it can be anticipated that also in a blocked design, where the direction of recall is manipulated in two conditions, the reversing will be performed during the encoding of the verbal material. In addition, given that the reversing operation at encoding is executively demanding, it can also be expected that an executive secondary task concurrently performed during the encoding phase, will differentially affect forward and backward verbal serial recall (such as in Vandierendonck, De Vooght, & Van der Goten, 1998a; 1998b). Conversely, given that the verbal demands are comparable for both directions of recall (Rosen & Engle, 1997), a verbal secondary task is anticipated to similarly affect forward and backward verbal serial recall.

Based on the previous considerations, the following predictions were formulated for the current experiment. First, since the choice RT task involves response selection whereas the simple RT task does not, we expected that the choice RT task would interfere more with forward and backward verbal serial recall than the simple RT task. Second, if response selection is executively controlled and not produced at the level of the verbal working memory slave system, we predicted that the choice RT task would impair backward verbal serial recall more adversely than forward verbal serial recall, while articulatory suppression would similarly affect both directions of recall. Before formulating the prediction associated with the simple RT task, we should point out that in all experiments reported in this study, the duration of the inter-stimulus intervals (ISIs) of the simple and choice RT tasks was pseudo-randomized, for the following two reasons. First, the inclusion of random ISIs induces executive demands in a simple RT task (Vandierendonck et al., 1998a). Such an executive control task is important in order to investigate whether a response selection process creates an additional executive load. Second, pseudo-random variable intervals reduce the probability that in a simple RT task, participants would respond based on anticipation rather than responding to the stimulus. Accordingly, we predicted that the simple RT task would also interfere more with backward than with forward verbal serial recall.

METHOD

Participants and Design. Forty-four first-year students enrolled at the Faculty of Psychology and Educational Sciences of Ghent University (Belgium) participated for course requirement and credit. They were randomly assigned to one of two reproduction instruction conditions (between-subjects: 21 participants in the forward and 23 in the backward recall condition), in which verbal serial recall was performed under a single-task condition and in concurrent execution with articulatory suppression, a choice RT task and a simple RT task. These within-subject conditions, which also included single-task simple RT and choice RT conditions, were counterbalanced according to a randomized Latin square.

***Materials and Procedure*.** The consonants were chosen from 13 groups with low intergroup confusability according to their Dutch pronunciation. The groups were: (B, D, P, T), (C), (F, S), (G), (H, K), (J), (L), (M, N), (Q), (R), (V, W), (X), (Z). A string of consonants was composed by selecting one letter at random from each group in order to minimize the phonological similarity between the letters. The RT tasks used two different and easily discriminable tones with a frequency of 262 (C1 note) and 524 Hz (C1 plus one octave). Each tone lasted 200 msec. For both RT tasks, the interval between two consecutive bleeps was either 900 or 1500 msec, randomly chosen with the constraint that no more than three consecutive intervals were of equal duration.

The participants were seated at an 80486 PC with a 15-inch color monitor. The instructions were presented on the computer screen and the experiment started with a practice session that consisted of two single trials. A trial started with the presentation of a fixation cross (+) in the center of the screen and a sound. After 500 msec the cross disappeared and after a 2000 msec blank screen, the first consonant was displayed for 1500 msec, followed by a 500 msec blank screen before the next consonant appeared. The sequence ended with a sound and three exclamation marks (‘!!!’) which were meant to trigger the reproduction. The participants were instructed to reproduce as many consonants as possible in the same or reverse order of presentation, according to their instruction condition. Oral recall was registered by the experimenter. At the end of reproduction, the experimenter started the next trial. After the two-trial practice, a verbal span task followed, which was also meant as a practice and was not included in the counterbalancing scheme. The verbal span task started with a sequence of three consonants and ended with a sequence of eight consonants. Three trials were presented per sequence; each participant performed 18 (6 sequences x 3) trials, regardless of their individual performance.

After the practice sessions, participants started with the six conditions that were included in the counterbalancing scheme. In the control condition, participants performed the verbal span task alone. In the dual-task conditions, participants had to perform a secondary task (simple RT task, choice RT task or articulatory suppression) during the presentation phase of the memory task but not during retrieval. The secondary tasks started 5000 msec before the primary task began and both primary and secondary tasks ended with the final sound that triggered primary task recall. For the simple RT task, participants were required to hit the 'zero' key on the numeric pad with the index finger of their right hand as fast as possible after they heard a tone. So as not to delay reaction time by movement time, the participants were instructed to rest the index finger of their right hand on the 'zero' key. During the choice RT task, participants were required to hit the 'one' key or the 'four' key on the numeric pad as fast as possible after they heard a low or a high frequency bleep, respectively. The participants were instructed to rest the index finger of their right hand on the 'one' key and their middle finger on the 'four' key to avoid target seeking movements between both keys. In the articulatory suppression condition, participants were required to continuously repeat aloud the word 'de' (Dutch for the). They were instructed and practiced so that the pace was not less than two and not more than three repetitions per second. The experimenter continuously verified that this pace was respected throughout the experiment. The remaining two conditions that were included in the counterbalancing scheme were a single-task simple RT and a single-task choice RT task condition (each for 12 periods of 20 seconds).

RESULTS

The performance on the RT tasks will be analyzed and discussed after all three experiments are presented. As dependent variable for the verbal memory task, we used a transformation of Kendall's rank correlation coefficient Tau, which reflects the proportion of stimuli recalled in correct relative order. This measure, τ', is obtained as follows:

$$\tau' = \frac{\sin^{-1}(\tau) + \pi/2}{\pi} \times \frac{n_r}{n}$$

where τ' is the Kendall rank correlation between the presented and the recalled order of items, n is the number of presented items and n_r is the number of recalled items. This formula yields an index between 0 and 1. Higher values denote many recalled items in correct order. Low values are obtained when the order is strongly violated or when only few items are recalled. Commission errors are not taken into account. The proportions of consonants recalled in correct relative order were expressed as a function of a 2 (Reproduction Instruction: forward and backward) x 4 (Condition: control, articulatory suppression, choice RT and simple RT) mixed design.

The data obtained from the three experiments reported in this paper were all analyzed by means of a repeated measures analysis based on the multivariate general linear model. The main effects of Reproduction Instruction, $F(1, 42) = 4.14$, $p < .05$, and Condition, $F(3, 40) = 121.31$, $p < .001$, were significant. The Reproduction Instruction x Condition interaction, $F(3, 40) = 3.24$, $p < .05$, was also significant. This interaction is displayed in Figure 1.

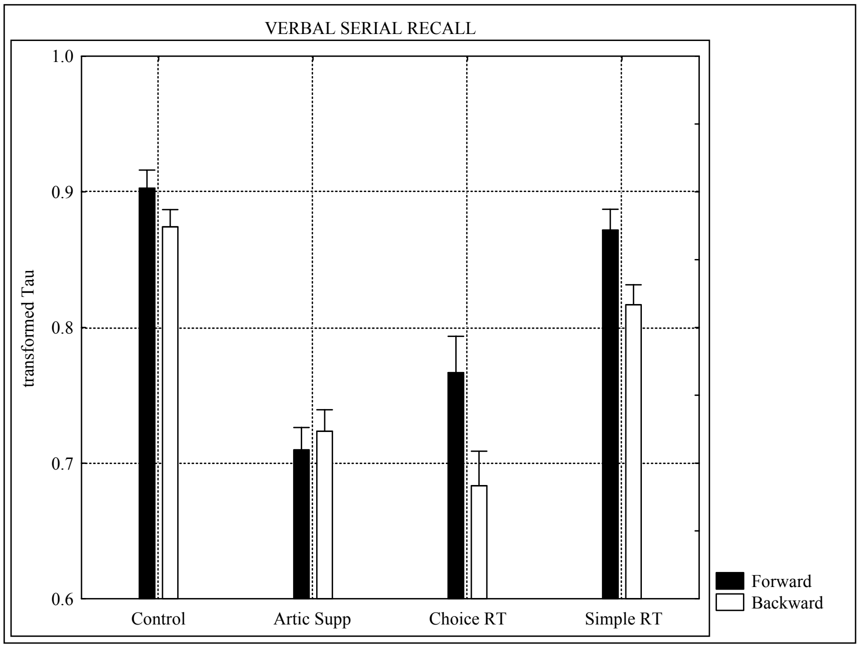

Figure 1. The proportion of consonants recalled in correct relative order (transformed Tau) as a function of the 2 (Reproduction Instruction: forward and backward) x 4 (Condition: control, articulatory suppression, choice RT and simple RT) mixed design (Experiment 1). Whiskers denote standard errors.

The predictions were tested by means of planned comparisons. These revealed that, under a single-task control condition, performance for forward and backward serial recall of consonants was comparable, $F(1, 42) = 2.36$, $p > .10$. Performance under articulatory suppression did not differ as a function of the Reproduction Instruction, $F < 1$: articulatory suppression affected both forward, $F(1, 42) = 188.26$, $p < .001$, and backward recall, $F(1, 42) = 125.51$, $p < .001$, in a similar way. Recall was also impaired by the concurrent choice RT task and this was larger for backward than for forward recall, $F(1, 42) = 5.07$, $p < .05$. The dual-task impairment due to the simple RT task was also larger for backward than for forward recall, $F(1, 42) = 6.70$, $p < .05$, replicating a finding reported by Vandierendonck et al. (1998a). The interaction of Reproduction Instruction with the planned contrast between Articulatory Suppression and the Choice RT task was significant, $F(1, 42) = 6.44$, $p < .05$. The interaction of Reproduction Instruction with the contrast between the Choice and the Simple RT task was not significant, $F < 1$.

DISCUSSION

In line with the earlier findings described in the introduction to this experiment, we observed that the simple RT task interfered more with backward than with forward verbal serial recall, whereas articulatory suppression similarly affected both directions of recall. With respect to the choice RT task, we observed that in both recall conditions, the choice RT task affected primary task performance more than the simple RT task did. In accordance with the predictions, the findings also showed that the adverse effects of the choice RT tasks were more pronounced when the primary task required backward compared to forward recall. Furthermore, with respect to the patterns of interference with forward and backward verbal serial recall, we observed a parallelism between the choice RT task and the simple RT task on the one hand, and a dissociation between articulatory suppression and the choice RT task on the other hand. The parallelism suggests that the choice RT task gives evidence of an executive pattern of interference and the dissociation indicates that the interference due to the choice RT task is not verbally mediated. Hence, we conclude that the choice RT task interferes more when the primary task requires more executive control and that the interference is not produced at the level of verbal working memory.

As we described in the introduction to this experiment, backward verbal serial recall is generally found to be poorer compared to forward verbal serial recall (but see Engle et al., 1999; Farrand & Jones, 1996). In the present study, we observed a similar level of performance for both directions of recall ($p = .13$). However, in the forward and backward verbal serial recall practice phase, which was always performed prior to the counterbalanced conditions (see Materials and Procedure), we did observe a difference in performance in favor of the forward condition (p = .02). This suggests that the difference between forward and backward recall might have disappeared through the practice effects associated with the completion of five (one practice and four counterbalanced conditions) verbal serial recall conditions in total. Interestingly, the additional executive demands associated with backward recall were not altered by practice. This shows that also when forward and backward recall yield similar levels of performance, the processing differences between both tasks remain measurable.

So far, the findings of Experiment 1 indicate that the interference effects of a task involving response selection are amplified when the executive load of the primary task is larger. Moreover, the interference does not seem to be produced at the level of the phonological slave system.

EXPERIMENT 2

The purpose of Experiment 2 was to further support the position that the choice RT task gives evidence of an executive pattern of interference and to examine the possibility that the interference from the choice RT task occurs at the level of the visuospatial working memory slave system. Accordingly, a short-term memory experiment was designed in which a simple RT task, a choice RT task and matrix tapping (i.e. a task that selectively interferes with visuospatial processing) were concurrently executed with a forward and a backward variant of the Corsi blocks task.

The Corsi blocks task requires participants to point to a series of blocks in the same (forward) or reversed (backward) order as presented by the experimenter. It is a popular measure of visuospatial serial recall which is considered to be the visuospatial counterpart of the verbal memory span task (for a review of the main findings, see Berch, Krikorian, & Huha, 1998). Despite the fact that both verbal and spatial serial recall were initially assumed to be equivalent measures of short-term memory, albeit in different modalities, there is a considerable amount of neuropsychological and experimental evidence that verbal and spatial serial recall are not similar in all respects (see Smyth & Scholey, 1992, for an extensive review).

Regarding the nature of the working memory processes involved in the forward version of the Corsi blocks task, it has been demonstrated that visuospatial and to a lesser extent also executive resources are deployed (Vandierendonck, Kemps, Fastame, & Szmalec, 2004; Vecchi & Richardson, 2001). Contrary to what holds for verbal span, it is a replicated finding that performance for spatial serial recall is not impaired by producing the items in reversed order (Isaacs & Vargha-Khadem, 1989; Vandierendonck et al., 2004; Wilde & Strauss, 2002). Smyth and Scholey (1992) attribute this to the fact that “in the spatial domain, it is possible for memory items to be maintained as a visuospatial pattern with no involvement of serial order” (p. 161). Hence, Smyth and Scholey (1992) suggested that whereas executive resources are required to reverse the order of presentation of verbal items, additional resources are not required to reverse the order of presentation of the spatial Corsi block items. This position is supported by the finding that an executive secondary task affects forward and backward recall of Corsi block sequences to a similar extent (Vandierendonck et al., 2004).

Another particularity of the Corsi blocks task is that the visuospatial demands seem to decrease in the backward version of the task. The latter position is supported by the observation that matrix tapping is more detrimental on forward than on backward recall (Vandierendonck et al., 2004) and by the neuropsychological finding that visuospatially impaired patients, compared to a group of matched controls, give evidence of a similar level of performance for the backward Corsi blocks task but lower performance for the forward version of the task (Mammarella, Cornoldi, & Donadello, 2003). Recently, Vandierendonck and Szmalec (in press) directly addressed the issue of decreased visuospatial resources in the backward

Corsi blocks task. They suggested that performance on the backward memorization of block sequences benefits from a recency effect in the sense that participants can recall the last three to four blocks without rehearsing them. This might explain why matrix tapping, a task that is known to interfere with the visuospatial rehearsal process (e.g. Logie, 1995), interferes less with the backward Corsi blocks task.

The evidence for a comparable executive involvement and a differential visuospatial involvement in forward and backward visuospatial serial recall tasks, suggests that it should be possible to dissociate visuospatial from executive involvement in an interference task concurrently executed with the forward and the backward Corsi blocks task. Accordingly, Experiment 2 aimed to dissociate executive from visuospatial processing involved in a choice RT task by means of comparing the interference of a choice RT task with the forward and backward Corsi blocks task, to the interference due to an executive control task and matrix tapping.

Based on the previous considerations, the following predictions were formulated. First, knowing that the Corsi blocks task involves executive control (Vandierendonck et al., 2004; Vecchi & Richardson, 2001), we expected that the choice RT task would interfere more with the Corsi blocks task than the simple RT task. Second, according to Vandierendonck et al. (2004) and the evidence discussed in the previous paragraphs, we anticipated that the executive control task (simple RT task) would similarly affect the forward and backward variants of the Corsi blocks task whereas matrix tapping would interfere more with the forward variant. Finally, if response selection is executively controlled and not produced at the level of the visuospatial working memory slave system, we would expect that the choice RT task, like the executive control task, would similarly affect the forward and the backward Corsi blocks task, and that the choice RT task would dissociate from matrix tapping in terms of interference with forward and backward visuospatial serial recall.

METHOD

Participants and Design. Fifty-three first-year students enrolled at the Faculty of Psychology and Educational Sciences of Ghent University (Belgium) participated for course requirement and credit. None of them had taken part in Experiment 1. They were randomly assigned to one of two reproduction instruction conditions (between-subjects: 28 participants in the forward and 25 in the backward reproduction instruction condition), in which the Corsi blocks tapping task was performed in a single-task condition and in concurrent execution with matrix tapping, a choice RT task and a simple RT task. These within-subject conditions, which also included single-task matrix tapping, choice RT and simple RT conditions, were counterbalanced according to a randomized Latin square.

Materials and Procedure. A computerized version of the Corsi blocks task was presented on a 15-inch touch screen. The 9 blocks were 30 x 30 mm white squares, positioned on a blue background according to Corsi's (1972) original configuration. The presentation of a block-sequence was monitored by the computer: each block in turn was highlighted by changing its color from white to black for 1 s, with an inter-block interval of 0.5 s.

The start of presentation was announced by a 400 msec 1000 Hz sound. The presentation ended with a 400 msec 100 Hz sound, which announced the reproduction phase. The participants were instructed to reproduce the highlighted blocks by touching the squares on the screen in the same or reverse order of presentation, depending on the condition they were assigned to. When a square was touched by the participant, it turned black for 200 msec in order to provide feedback on the touching operation. At the end of recall, the participant was required to hit the escape key and after a 2s inter-trial interval, the next trial started. A condition started with a sequence of three and ended with a sequence of eight blocks. Three trials were presented at each sequence length, so each condition consisted of 18 trials.

Instructions were presented on the computer screen. The experiment started with two practice trials and an entire single-task Corsi practice block, followed by the seven counterbalanced conditions. In the control condition, participants performed the Corsi block-tapping task alone. In the dual-task conditions, the secondary tasks (matrix tapping, the choice RT task and the simple RT task) were executed during the presentation of the Corsi block sequences but not during retrieval. Matrix tapping required the participants to hit the four corners of the numeric keypad in counterclockwise order at a pace of 2-3 keys per second. This operation was registered in terms of accuracy and latency. The other secondary tasks were the same as in Experiment 1. Performance on the three secondary tasks was also registered in a single-task situation (each task for 12 periods of 20 seconds).

RESULTS

Using the same measure as in Experiment 1 (τ'), the proportion of consonants recalled in correct relative order was expressed as a function of a 2 (Reproduction Instruction: forward and backward) x 4 (Condition: control, matrix tapping, choice RT and simple RT) mixed design. The main effect of Reproduction Instruction was not significant, $F < 1$, while the main effect of Condition was, $F(3, 49) = 61.15$, $p < .001$. The interaction Reproduction Instruction x Condition, $F(3, 49) = 6.68$, $p < .001$, was also significant. Figure 2 displays the interaction.

Planned comparisons showed that, in the single-task control condition, performance was comparable for both forward and backward serial recall of Corsi blocks, $F < 1$. Matrix tapping affected both forward, $F(1, 51) = 96.73$, $p < .001$, and backward recall, $F(1, 51) = 30.42$, $p < .001$, of block sequences but the interference was significantly stronger for forward than for backward recall, $F(1, 51) = 7.54$, $p < .01$. The choice RT task interfered with forward, $F(1, 51) = 54.97$, $p < .001$, and backward, $F(1, 51) = 74.25$, $p < .001$, recall of Corsi block sequences. The degree of interference was comparable for both reproduction instruction conditions, *F*(1, 51) = 1.22, *p* > .10. The simple RT task did not affect forward recall, *F*(1, 51) = 2.46, *p* > .10, while it did impair backward recall, *F*(1, 51) = 19.40, *p* < .001. However, the difference in simple RT task interference between both directions of recall failed to reach statistical significance, *F*(1, 51) = 3.93, *p* > .05. Furthermore, the interaction of Reproduction Instruction with the contrast between Matrix Tapping and the Choice RT task was significant, *F*(1, 51) = 12.08, *p* < .01, while the interaction of Reproduction Instruction with the contrast between the Choice and the Simple RT task was not, *F* < 1.

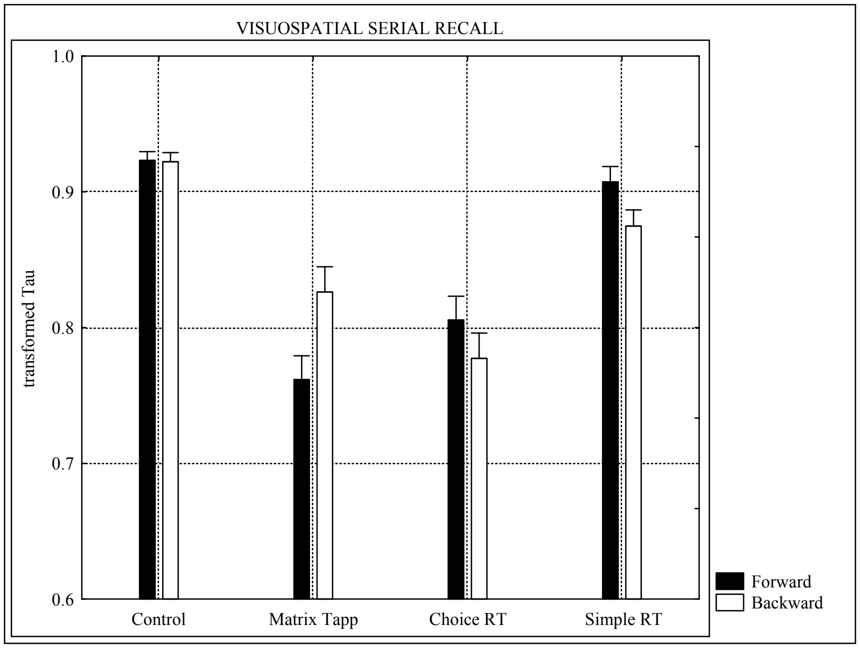

Figure 2. The proportion of blocks recalled in correct relative order (transformed Tau) as a function of the 2 (Reproduction Instruction: forward and backward) x 4 (Condition: control, matrix tapping, choice RT and simple RT) mixed design (Experiment 2). Whiskers denote standard errors.

DISCUSSION

Experiment 2 replicated the findings reported by Vandierendonck et al. (2004) and further demonstrated that, in terms of interference with the forward and backward variants of the Corsi blocks task, the response selection task dissociated from a visuospatial task but gave evidence of a similar pattern of interference as the executive control task. Accordingly, in line with the findings of Experiment 1 for the verbal domain, we can conclude that the choice RT task does not interfere at the level of the VSSP, but probably does at the level of the Central Executive.

EXPERIMENT 3

So far, we have demonstrated that response selection contributes to a dual-task impairment which is not situated at the level of the slave systems. If response selection is not produced at the level of verbal or visuospatial processing, what is the basis of the observed effects? We have suggested that the interference is mediated by executive control, based on the observation that the impairment of the choice RT task on verbal and visuospatial serial recall is comparable to a pattern of interference observed with another executive secondary task. Nevertheless, more direct evidence is needed to support the latter position. However, this additional evidence is more likely to be obtained with other tasks than verbal or visuospatial serial recall tasks. The reason is that the extent to which those serial recall tasks involve executive control is rather limited (see Engle et al., 1999). Thus, in spite of the fact that those verbal and visuospatial span tasks are useful to dissociate executive from domain-specific processing, which was the main purpose of Experiments 1 and 2, a more demanding measure of executive control is needed to evidence the specifically executive demands of response selection more directly. Therefore, Experiment 3 used a well-established neuropsychological measure with high executive demands, namely verbal fluency (e.g. Phillips, 1997; Rende, Ramsberger, & Miyake, 2002).

Verbal fluency usually requires a person to generate as many words as possible with a specified initial letter (letter fluency) or from a specified category (category fluency). Although verbal fluency was initially considered to be a relatively pure measure of frontal or executive functioning (e.g. Denckla, 1994), Rende et al. (2002) demonstrated that verbal and visuospatial processes also contribute to letter and category fluency, albeit in a different way. More precisely, the Phonological Loop seems to contribute to letter fluency while the Visuospatial Sketch Pad plays a similar role in category fluency. With respect to the executive contribution to verbal fluency, Rende et al.'s findings showed that the executive function of 'mental set shifting' is equally involved in letter and category fluency tasks.

Taking into account these findings, a number of predictions were formulated for Experiment 3. First, if response selection involves executive control, a concurrent choice reaction task should have a more disruptive effect on a task that requires many executive resources (i.e. verbal fluency) than concurrent simple reaction. The second prediction refers to the processing differences between letter and category fluency, as reported by Rende et al. (2002). If response selection is not mediated by verbal or spatial processing, the choice RT task is predicted not to differentially affect letter and category fluency. That is why the choice RT task is instead expected to cause a more general impact on verbal fluency, analogous to the arithmetic switching task that was used to operationalize the executive function 'task set shifting', in the study of Rende et al. (2002).

METHOD

Participants and Design. Twenty-four first-year students enrolled at the Faculty of Psychology and Educational Sciences of Ghent University (Belgium) participated for course requirements and credit. None of them had taken part in any of the previous experiments. The participants were randomly assigned to one of two between-subjects conditions of a 2

(Executive Task: simple and choice RT) x 2 (Condition: single and dual-task) x 2 (Fluency Task: letter and category fluency) mixed design with repeated measures on the last two factors.

Materials and Procedure. Letter and category fluency tasks were used. A letter fluency task requires participants to produce nouns or verbs beginning with a specified letter. Category fluency requires the participants to generate as many items as possible from a specified category (e.g. animals). In the present experiment, 14 fluency tasks were used: 8 letter fluency (4 nouns with N, A, K, B; 4 verbs with V, D, T, K) and 6 category fluency (flowers, fruits, animals, articles of clothing, names for girls, names for boys) tasks.

The participants were seated at an 80486 PC with a 15-inch color monitor. The instructions were presented on the computer screen. Each subject performed the 14 verbal fluency tasks: 7 under single-task and 7 concurrently with either simple or choice reaction, depending on which condition they were assigned to. The tasks were counterbalanced over the conditions contrasting single and dual-task verbal fluency performance and with the two kinds of verbal fluency represented equally in both conditions. In other words, the 7 tasks in the control condition and the 7 tasks concurrently executed with either simple or choice reaction, consisted of 4 letter (2 nouns and 2 verbs) and 3 category fluency tasks that were counterbalanced over the conditions. Half of the participants started with the single-task verbal fluency tasks, the other half with the dual-task conditions.

The fluency task was centered on the computer screen. 2000 milliseconds later, the word ‘START’ flickered on the screen to signal the beginning of the verbal fluency task. At this point, the participants generated as many verbal items as possible within 45 seconds. The words were taped by means of an audio recorder. The end of the fluency task was announced by a 100 Hz tone.

In the dual-task conditions, the simple or choice reaction task was started 5000 msec before the fluency task. After this single-task period, the task and the start-signal were presented following the same procedure, and from this point, both tasks were performed concurrently until the final sound. Each participant also performed the simple and choice RT task in a single-task condition for a period of 45 sec.

RESULTS

The number of words produced per 45 seconds as a function of the 2 (Executive Task: simple and choice RT task) x 2 (Condition: single and dual-task) x 2 (Fluency Task: letter and category fluency) mixed design was subjected to a repeated measures analysis based on the multivariate general linear model (see Table 1). The main effect of Executive Task was not significant, $F(1, 22) = 1.33$, $p > .10$, while the main effects of Condition and Fluency Task were, $F(1, 22) = 30.82$, $p < .001$, and, $F(1, 22) = 49.08$, $p < .001$, respectively. The interaction of Executive Task and Condition was significant, $F(1, 22) = 19.51$, $p < .001$, while the three-way interaction of Executive Task, Condition and Fluency Task was not, $F < 1$. Further planned comparisons revealed that the simple RT task affected neither letter fluency, $F < 1$, nor category fluency, $F(1, 22) = 1.82$, $p > .10$. In contrast, the choice RT task clearly affected both letter, $F(1, 22) = 47.72$, $p < .001$, and category fluency, $F(1, 22) = 22.74$, $p < .001$. Finally, the absence of an interaction between the factors Condition and Fluency Task in the choice RT task group, $F < 1$, shows that the choice RT task similarly affected letter and category fluency.

	Letter Fluency		Category Fluency	
	Single-Task	Dual-Task	Single-Task	Dual-Task
Simple RT task	7.50 (1.85)	7.85 (2.24)	15.47 (4.14)	13.80 (3.87)
Choice RT task	9.23 (2.23)	5.77 (1.65)	15.75 (3.06)	9.86 (2.18)

Table 1. The mean number of words produced per 45 seconds as a function of Executive Task (simple and choice RT task), Condition (single and dual-task) and Fluency Task (letter and category fluency). Standard deviations in parentheses.

DISCUSSION

The results of Experiment 3 show that the choice RT task interferes with verbal fluency while the simple RT task does not. Since both RT tasks differ in terms of response selection demands, the conclusion that response selection affects verbal fluency is straightforward. The choice RT task effects were also considered separately for the letter fluency and category fluency tasks. According to Rende et al. (2002), if response selection is mediated by a subsidiary component of working memory, the choice RT task should differentially affect letter and category fluency performance. However, we observed that the decrement in fluency performance due to the concurrent choice reaction task was similar for the different variants of the fluency task. In other words, the choice RT task caused this more general impairment on verbal fluency, which has been observed with another executive secondary task (e.g. Rende et al., 2002). For these reasons, the findings of Experiment 3 support our hypothesis that response selection involves executive control in a way that does not involve any of the subcomponents of working memory in a detectable manner. It is also important to mention that the simple RT task did not affect verbal fluency at all. An explanation for this finding will be given in the General Discussion section.

RESULTS OF RT TASK PERFORMANCE ANALYSIS

Performance on the simple and choice RT tasks was analyzed in order to investigate whether the RT tasks were also affected under dual-task conditions, or in other words, to make sure that our findings cannot be explained by dual-task tradeoffs. Because the dual-task analysis revealed a similar pattern of results in all three experiments, we decided to pool the three data sets.

The reaction time data show that both the simple and the choice RT task were affected under dual-task conditions. Performance on the simple RT task was delayed from 273 msec (SD = 56.66) under single-task to 369 msec (SD = 93.55) under dual-task conditions. This 35% delay was statistically reliable, $F(1, 108) = 184.91$, $p < .001$. Similarly, performance on the choice RT task was delayed from 453 msec (SD = 73.01) under single-task to 530 msec (SD = 97.87) under dual-task conditions, a 17% delay which was also statistically significant, $F(1, 108) = 115.52$, $p < .001$. The interaction of the Simple vs. Choice RT task contrast and the Single-Task vs. Dual-Task contrast was also significant, $F(1, 108) = 6.49$, $p < .05$. This shows that the dual-task effect on the simple RT task was stronger than on the choice RT task.

From these analyses, it is clear that the dual-task setting affected both the primary memory tasks and the secondary RT tasks. This implies that no dual-task tradeoff occurred. The observation that the simple RT task was more adversely affected in a dual-task setting than the choice RT task replicates earlier findings of Frith and Done (1986), who also observed a greater dual-task cost in reaction time performance for a simple (24%) compared to a choice RT task (8%). Such results are taken to indicate that simple and choice RT tasks follow different neural routes, and thus are considered to be qualitatively different (see also Berns & Sejnowski, 1996; Rowe et al., 2000; Schubert, 1999). A final remark is related to the longer processing time observed in choice reaction compared to simple reaction.

This suggests that, in addition to the augmented executive demands, the increased processing time might also have contributed to the additional dual-task interference due to response selection.

GENERAL DISCUSSION

The present study compared the patterns of dual-task interference of a simple and a choice RT task to determine whether response selection involves executive control. Experiment 1 demonstrated that a choice RT task gives evidence of an executive pattern of dual-task interference with forward and backward verbal serial recall and that this interference is not produced at the level of working memory's verbal slave system. Similarly, Experiment 2 demonstrated that, also in concurrent execution with forward and backward visuospatial serial recall, a choice RT task gives evidence of an executive pattern of dual-task interference and that this interference is not produced at the level of working memory's visuospatial slave system. Finally, Experiment 3 demonstrated that a choice RT task causes additional interference with executive control compared to a simple RT task. Altogether, these findings show that response selection interferes with primary tasks that require executive control and that the interference is not produced at the level of the domain-specific verbal or visuospatial slave systems. Following the logic of the selective interference paradigm within a working memory framework, this means that the response selection process involves executive control.

A point that requires some elaboration is the observation that in Experiments 1 and 2, the secondary task effects were obtained during the encoding and acquisition phase of a short-term memory task, whereas in Experiment 3, the effects were obtained during the retrieval of elements from long-term memory. This distinction is important because a number of studies by Naveh-Benjamin and colleagues have observed an asymmetry in attentional involvement between encoding and retrieval (e.g. Naveh-Benjamin, Craik, Guez, & Dori, 1998). They argued that “whereas encoding processes are controlled, retrieval processes are obligatory but do require attentional resources for their execution” (Naveh-Benjamin et al., 1998, p. 1091). These authors claim that encoding processes are consciously controlled and attention demanding. Retrieval processes, however, appear to be more protected in the sense that under conditions of divided attention, the secondary task pays the entire dual-task cost. The present data fit well into this view of attentional involvement at encoding and retrieval. Our simple RT task affected the encoding of consonants and Corsi block positions and while it did not hinder the retrieval of verbal fluency items, the RT task itself was clearly affected. The choice RT task severely impaired encoding in the verbal and visuospatial span experiments and it also impaired the retrieval of verbal fluency items. The finding that choice reactions affect memory retrieval is not a new one (Carrier & Pashler, 1995; Rohrer & Pashler, 2003). However, it remains debatable whether the interference between response selection and retrieval originates from a structural bottleneck at response selection or from a shortfall in attentional resources when two attentional demanding tasks are simultaneously executed (see also Barrouillet, Bernardin, & Camos, 2004).

A further important matter with respect to the current results is the issue of task difficulty. It is a fact that a manipulation of cognitive processing affects the difficulty of a task, by which a potential confound for the interpretation of the results is induced. In this debate, a number of researchers have argued that ‘difficulty’ cannot be put forward as a true alternative explanation for a manipulation effect, provided that the reason(s) for the differences in task difficulty are known. When the differences in task difficulty can be explained in terms of established qualitative processing differences, ‘task difficulty’ becomes “merely a descriptor of a manipulation’s consequence” (e.g. Garavan, Ross, Li, & Stein, 2000). In this view, the theoretical and empirical developments supporting the view of qualitative processing differences between simple and choice RT tasks (Berns & Sejnowski, 1996; Frith & Done, 1986; Rowe et al., 2000; Schubert, 1999), make an alternative interpretation for the present findings, based on task difficulty, less plausible.

Finally, what are the implications of the present results for current views on executive functioning? First of all, while a few studies have already reported neuroimagery (Rowe et al., 2000) and electromyographic (Allain et al., 2004) findings suggesting that executive control is involved in response selection, the current study is the first to present converging evidence from a behavioral paradigm. In this sense, it supports the idea that executive control occurs at much more fundamental levels of human cognition than initially proposed by means of higher level concepts such as planning or problem solving. Secondly, the present findings also challenge the notion of a unitary executive controller such as the Central Executive (Baddeley, 1996; Miyake et al., 2000). In this regard, we prefer to look at executive control as a concept that stands for the combined action of a number of processes (such as monitoring, inhibition, updating and response selection), which are crucial to achieve an intended thought or behavior. Thirdly, and maybe most importantly given the current lack of paradigms to study executive control (Barnard, Scott, & May, 2001), the present study has demonstrated that the selective interference paradigm seems to be a useful tool to investigate executive functioning. The potential of this paradigm for exploring other candidate executive processes awaits further exploitation.

REFERENCES

Allain, S., Carbonnell, L., Burle, B., Hasbroucq, T., & Vidal, F. (2004). On-line executive control: An electromyographic study. *Psychophysiology, 41*, 113-116.

Ashman, A. F., & Das, J. P. (1980). Relation between planning and simultaneous-successive processing. *Perceptual & Motor Skills, 51*, 371-382.

Baddeley, A. D. (1986). *Working Memory*. Oxford: Oxford University Press, Clarendon Press.

Baddeley, A. D. (1996). Exploring the Central Executive. *Quarterly Journal of Experimental Psychology, 49A*, 5-28.

Barnard, P. J., Scott, S. K., & May, J. (2001). When the Central Executive lets us down: Schemas, attention, and load in a generative working memory task. *Memory, 9*, 209-221.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General, 133*, 83-100.

Berch, D. B., Krikorian, R., & Huha, E. M. (1998). The Corsi block-tapping task: Methodological and theoretical considerations. *Brain & Cognition, 38*, 317-338.

Berns, G. S., & Sejnowski, T. J. (1996). How the basal ganglia make decisions. In A. R. Damasio (Ed.), *Neurobiology of decision-making* (pp. 101-113). Berlin: Springer-Verlag.

Bunge, S. A., Hazeltine, E., Scanlon, M. D., Rosen, A. C., & Gabrieli, J. D. (2002). Dissociable contributions of prefrontal and parietal cortices to response selection. *Neuroimage, 17*, 1562-71.

Carrier, L. M., & Pashler, H. (1995). Attentional limits in memory retrieval. *Journal of Experimental Psychology: Learning Memory & Cognition, 21*, 1339-1348.

Case, R., & Globerson, T. (1974). Field independence and central computing space. *Child Development, 45*, 772-778.

Denckla, M. (1994). Measurement of executive function. In G. R. Lyon (Ed.), *Frames of reference for the assessment of learning disabilities. New views on measurement issues* (pp. 117-142). Baltimore: Paul H. Brookes Publishing Company.

Donders, F. C. (1868/1969). 'Over de snelheid van psychische processen' [On the speed of mental processes; translated by W.G. Koster]. In: W.G. Koster (ed.), Attention and performance II. *Acta Psychologica, 30*, 412-431.

Elliot, C. D., Smith, P., & McCulloch, K. (1997). *British Ability Scales II. Technical Manual*. Windsor, UK: NFER-Nelson.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128*, 309-331.

Farrand, P., & Jones, D. (1996). Direction of report in spatial and verbal serial short-term memory. *Quarterly Journal of Experimental Psychology, 49A*, 140-158.

Frith, C. D., & Done, D. J. (1986). Routes to action in reaction-time tasks. *Psychological Research, 48*, 169-177.

Garavan, H., Ross, T. J., Li, S. J., & Stein, E. A. (2000). A parametric manipulation of central executive functioning. *Cerebral Cortex, 10*, 585-592.

Gathercole, S. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Science, 3*, 410-418.

Gathercole, S., & Pickering, S. J. (2000). Working memory deficits in children with low achievements in the national curriculum at 7 years of age. *British Journal of Educational Psychology, 70*, 177-194.

Groeger, J. A., Field, D., & Hammond, S. M. (1999). Measuring memory span. *International Journal of Psychology, 34*, 359-363.

Hegarty, M., Shah, P., & Miyake, A. (2000). Constraints on using the dual-task methodology to specify the degree of central executive involvement in cognitive tasks. *Memory & Cognition, 28*, 376-385.

Hinrichs, J. V. (1968). Prestimulus and poststimulus cueing of recall order in the memory span. *Psychonomic Science, 12*, 261-262.

Isaacs, E. B., & Vargha-Khadem, F. (1989). Differential course of development of spatial and verbal memory span: A normative study. *British Journal of Developmental Psychology, 7*, 377-380.

Jensen, A. R., & Figueroa, R. A. (1975). Forward and backward digit span interaction with race and IQ: Predictions from Jensens theory. *Journal of Educational Psychology, 67*, 882-893.

Klauer, K. C., & Stegmaier, R. (1997). Interference in immediate spatial memory: Shifts of spatial attention or central-executive involvement? *Quarterly Journal of Experimental Psychology, 50A*, 79-99.

Lezak, M. D. (1995). *Neuropsychological assessment.* New York: Oxford University Press.

Logie, R. H. (1995). *Visuo-spatial working memory.* Hillsdale: Erlbaum.

Mammarella, N., Cornoldi, C., Donadello, E. (2003). Visual but not spatial working memory deficit in children with spina bifida. *Brain & Cognition, 53*, 311-314.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41,* 49-100.

Naveh-Benjamin, M., Craik, F. I. M., Guez, J., & Dori, H. (1998). Effects of divided attention on encoding and retrieval processes in human memory: Further support for an asymmetry. *Journal of Experimental Psychology: Learning Memory & Cognition, 24*, 1091-1104.

Nilsson, L. G., Wright, E., & Murdock, B. B. (1979). Order of recall, output interference, and the modality effect. *Psychological Research, 41*, 63-78.

Phillips, L. H. (1997). Do "frontal tests" measure executive function? Issues of assessment and evidence from fluency tests. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 191-214). Hove, UK: Psychology Press.

Rabbitt, P. (1997). *Methodology of frontal and executive function*. Hove, UK: Psychology Press.

Rende, B., Ramsberger, G., & Miyake, A. (2002). Commonalities and differences in the working memory components underlying letter and category fluency tasks: A dual-task investigation. *Neuropsychology, 16*, 309-321.

Rohrer, D., & Pashler, H. E. (2003). Concurrent task effects on memory retrieval. *Psychonomic Bulletin & Review, 10*, 96-103.

Rosen, V. M., & Engle, R. W. (1997). Forward and backward serial recall. *Intelligence, 25*, 37-47.

Rowe, J. B., Toni, I., Josephs, O., Frackowiak, R. S. J., & Passingham, R. E. (2000). The prefrontal cortex: Response selection or maintenance within working memory? *Science, 288*, 1656-1660.

Schofield, N. J., & Ashman, A. F. (1986). The relationship between digit span and cognitive processing across ability groups. *Intelligence, 10*, 59-73.

Schubert, T. (1999). Processing differences between simple and choice reactions affect bottleneck localization in overlapping tasks. *Journal of Experimental Psychology: Human Perception & Performance, 25*, 408-425.

Smyth, M. M., & Scholey, K. A. (1992). Determining spatial span: The role of movement time and articulation rate. *Quarterly Journal of Experimental Psychology, 45A*, 479-501.

Smyth, M. M., & Scholey, K. A. (1994). Interference in immediate spatial memory. *Memory & Cognition, 22*, 1-13.

Vandierendonck, A., De Vooght, G., & Van der Goten, K. (1998a). Interfering with the Central Executive by means of a Random Interval Repetition task. *Quarterly Journal of Experimental Psychology, 51A*, 197-218.

Vandierendonck, A., De Vooght, G., & Van der Goten, K. (1998b). Does random time interval generation interfere with working memory executive functions? *European Journal of Cognitive Psychology, 10*, 413-442.

Vandierendonck, A., Kemps, E., Fastame, M.C., & Szmalec, A. (2004). Working memory components of the Corsi blocks task. *British Journal of Psychology, 95, 57-79.*

Vandierendonck, A., & Szmalec, A. (in press). An asymmetry in the visuospatial demands of forward and backward recall in the Corsi blocks task. *Imagination, Cognition & Personality*.

Vecchi, T., & Richardson, J. T. E. (2001). Measures of visuospatial short-term memory: The Knox cube imitation test and the Corsi blocks test compared. *Brain & Cognition, 46*, 291-294.

Wilde, N., & Strauss, E. (2002). Functional equivalence of Wais-Iii/Wms-Iii digit and spatial span under forward and backward recall conditions. *Clinical Neuropsychologist, 16*, 322-330.

.

CHAPTER 3
ESTIMATING THE EXECUTIVE DEMANDS OF A ONE-BACK CHOICE RT TASK BY MEANS OF THE SELECTIVE INTERFERENCE PARADIGM

***Manuscript under revision*[1]**

The present study implements the selective interference paradigm to estimate the executive demands of the processing components involved in a one-back choice reaction time (RT) task. Based on the similarities between a one-back choice RT task and the running memory or *n*-back updating procedure, it was hypothesized that one-back delaying of a choice reaction involves executive control. In three experiments, framed within Baddeley's (1986) working memory model, a one-back choice RT task, a choice RT task, articulatory suppression and matrix tapping were performed concurrently with primary tasks involving verbal, visuospatial or executive processing. The results demonstrate that one-back delaying of a choice reaction interferes with executive control and that the interference is neither mediated by the verbal nor by the visuospatial working memory slave system. The implications of these results for our views on executive control in general are discussed.

---

[1] This paper was co-authored by André Vandierendonck

INTRODUCTION

The term "executive" refers to a supervisory attentional control system that orchestrates the operation of several cognitive processes. To date, most cognitive (neuro)psychologists agree on the types of situations which require executively controlled processing (especially difficult, problematic and novel situations) but the nature of executive control itself remains less clear. The last years have witnessed a noticeable focus on executive functioning. This movement is partly a result of a few studies which have comprehensively summarized the unsatisfactory state of affairs in executive/frontal function research (Baddeley, 1996; Rabbitt, 1997).

A number of empirical attempts at clarifying the concept of executive control have used Baddeley's Working Memory (WM) model as a theoretical framework. The original WM model (Baddeley & Hitch, 1974; Baddeley, 1986) proposes that working memory comprises a modality-free control system, the Central Executive, and two domain-specific slave systems which are supervised by this executive control system. One slave system, the Phonological Loop, is responsible for the manipulation and short-term maintenance of verbal information while the other slave system, the Visuospatial Sketch Pad, fulfills a similar role for visuospatial information. In this model, executive control was conceived as a unitary system, represented by the notion of the Central Executive. During the last years, this unitary character has been challenged (Baddeley, 1996; Baddeley, 2000) and in this vein, a correlational study by Miyake, Friedman, Emerson, Witzki, Howerter and Wager (2000) clearly demonstrated that the executive functions of inhibition, updating and mental set shifting are separable but also interrelated. In accordance with this evidence, the working memory notion of executive control is nowadays preferably typified by both unity and diversity.

It is beyond doubt that the nowadays popular executive functions are more fundamental and purer measures of executive control than the ill-defined concepts of planning and problem solving which were usual at the onset of executive/frontal function research. However, the conclusion that the executive functions of updating, inhibition and shifting are both separable and interrelated, suggests that the tasks which measure those functions involve processes which are unique to the task, as well as processes which are shared with other executive tasks. This raises the question whether those executive functions reflect basic executive processing or whether they are each made up of several more fundamental processes which are not all necessarily executive in nature.

One such more fundamental process which is involved in nearly all executive functions is response selection. An increasing number of empirical findings suggest that executive control might be involved in response selection (Allain, Carbonnell, Burle, Hasbroucq, & Vidal, 2004; Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Hegarty, Shah, & Miyake, 2000; Klauer & Stegmaier, 1997; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000). In a recent study, we presented additional behavioral evidence for this assumption (Szmalec, Vandierendonck, & Kemps, in press). The patterns of selective interference of a simple and a choice RT task were compared, relative to the effects of verbal and visuospatial secondary tasks, in concurrent execution with verbal, visuospatial and executive primary tasks. It was concluded that the additional demands of a choice RT task, compared to a simple RT task, interfere with executive control and that the interference is not produced at the level of the WM slave systems.

PRESENT STUDY

In view of the current lack of paradigms to study executive functioning (Barnard, Scott, & May, 2001; Van der Linden, Collette, Salmon, Delfiore, Degueldre, Luxen et al., 1999), the purpose of the present study is to further exploit the potential of the selective interference paradigm to contribute to a clarification of the concept of executive control. The central idea is to design interference tasks in which particular – presumably executive – parameters are varied and to estimate the executive demands of the processing components associated with this parametric variation. Szmalec et al. (in press) used an established parametric variation, namely simple versus choice reaction (e.g. Schubert, 1999), to demonstrate that response selection involves executive control. The present study uses the selective interference paradigm for estimating the executive demands associated with other, less well understood but presumably executive parametric variations of interference tasks. Our basic assumption is that a better understanding of the parametric variations that affect the executive demands of a task can be useful to gain insight into the notion of "executive system" itself. For that purpose, the current study presents a parametric variation on the choice RT task, namely the one-back choice RT task, and it uses the selective interference paradigm to estimate the effect of this manipulation in terms of executive demands. As will be described in the following paragraphs, there are theoretical reasons to assume that a one-back choice RT task requires executive control in addition to the executive demands involved in response selection.

A one-back choice RT task requires participants to make a choice reaction on a stimulus x with the particular demand to delay the response until the occurrence of the next stimulus x+1 (one-back). It implies that, during the inter-stimulus interval, participants have to keep an active representation of the information that will be necessary in order to make a correct choice reaction to stimulus x after stimulus x +1 is presented. This means that as soon as stimulus x+1 is presented, the response to the previous stimulus x is executed and the active representation is updated or refreshed with the information that will be necessary to make a correct choice reaction to stimulus x+1 when stimulus x+2 will be presented, and so on. In this way, the participants need to hold a representation of task-relevant information active throughout the task and they need to update this representation each time new information (i.e. a new stimulus) is presented.

The one-back choice RT task bears strong similarities to the running memory or *n*-back updating procedure, which was originally put forward by Pollack, Johnson & Knaft (1959) and further elaborated by Morris and Jones (1990). In the Morris and Jones *n*-back task participants are presented a list of consonants of unknown length. During this presentation, they are required to remember a specified number (n) of the most recent consonants serially (*n*-back). This implies that, while the task evolves and new items are presented, the subjects have to update the memorized string of n most recent items: they need to drop the oldest item in the string and add the most recent one. Morris and Jones (1990) demonstrated that most probably the Central Executive is responsible for the updating process involved in the *n*-back task. During the last decade, the *n*-back task has proven to be a widely used measure of working memory performance and at the same time a popular operationalization of the executive function of updating (e.g. Smith & Jonides, 1999; Miyake et al., 2000; Smith-Spark, Fisk, Fawcett, & Nicolson, 2003; Van der Linden et al., 1999).

Based on the descriptions of the one-back choice RT task and the Morris and Jones updating task, it can be argued that both tasks involve the updating of task-relevant information each time a new stimulus is presented. Accordingly, following the theoretical position that also a one-back choice RT task requires updating and on the assumption that the process of updating is executive in nature (Morris & Jones, 1990), it can be hypothesized that the one-back choice RT task involves executive control. However, in the light of recent findings supporting an executive involvement in a choice RT task (Allain et al., 2004; Rowe et al., 2000; Szmalec et al., in press), there is another potential source of executive involvement in a one-back choice RT task compared to a choice RT task, which must be considered. Allain et al. (2004) found electromyographic indicators for an online executive supervision of the processing involved in a choice RT task and they demonstrated that these indicators were measurable until the final execution of the response. Since this execution is delayed in a one-back choice RT task ─ a delay during which the task-relevant information is kept active ─ it can be hypothesized that also the executive supervision is prolonged, by which a one-back choice RT task is anticipated to give evidence of quantitatively increased executive demands compared to a choice RT task.

The present study uses the selective interference paradigm within Baddeley's tripartite model of working memory to investigate whether one-back delaying of a choice reaction involves executive control. Accordingly, the nature of the interference due to the one-back delaying of a choice reaction is estimated by comparing a standard and a one-back choice RT task as sources of interference with a number of working memory tasks that operationalize the three components of the WM model. The rationale of the experiments is as follows: if a process is executive in nature, it is expected to interfere with primary tasks that involve executive control while it must be demonstrated that this interference is not produced by the working memory slave systems. Experiment 1 compares the patterns of dual-task interference of a one-back and a standard choice RT task on two often used measures of executive control, namely letter and category fluency, in order to demonstrate that a one-back choice reaction interferes more with a primary task that requires executive control, than a standard choice reaction. Experiment 2 is aimed to demonstrate that the additional interference of the one-back choice reaction is not produced at the level of the Phonological Loop. Therefore, it compares the patterns of dual-task impairment of a one-back and a standard choice RT task, relative to the effects of a secondary task that selectively interferes with verbal processing (i.e. articulatory suppression), on forward and backward serial recall of consonants. Experiment 3 was designed to show that the Visuospatial Sketch Pad does not mediate the effect either, by comparing the patterns of dual-task impairment of a one-back and a standard choice RT task, relative to the effects of a secondary task that selectively interferes with visuospatial processing (i.e. matrix tapping), on forward and backward serial recall of visuospatial positions (i.e. Corsi blocks task).

EXPERIMENT 1

Experiment 1 was set up in order to test whether one-back delaying of a choice reaction interferes with an executively demanding primary task. To this end, the one-back and the standard choice reaction time tasks were concurrently executed with a task that is known to involve high executive demands, namely verbal fluency. Verbal fluency has been used extensively in cognitive psychology and neuropsychology in order to assess executive or frontal (dys)functioning (Phillips, 1997; Baddeley, Lewis, Eldridge, & Thomson, 1984; Baddeley, Emslie, Kolodny, & Duncan, 1998; Martin, Wiggs, Lalonde, & Mack, 1994; Rosen & Engle, 1997). The task requires a participant to generate as many verbal items as possible within a predefined period of time. In the most popular variants of the task, these verbal items are nouns beginning with a specified letter (i.e. letter fluency) or members from a specified semantic category (i.e. category fluency). Several researchers have recommended verbal fluency as an easy and reliable measure of executive functioning (e.g. Denckla, 1994; Parker & Crawford, 1992), while others have expressed some concerns about the task, in the sense that not all variants of verbal fluency seem to be reliable measures of executive control (Phillips, 1997; Reitan & Wolfson, 1994). Phillips (1997), for example, demonstrated that an executive task such as random number generation task affected figural fluency (i.e. producing as many different figures as possible) but not letter fluency, which suggests that the Central Executive is not involved in letter fluency, at least not to an extent that is measurable by the executive demands of a random number generation. Such findings imply that the Central Executive is not equally involved in all variants of the verbal fluency task. More recent studies have established that the processing differences between the different types of verbal fluency reach further than merely quantitative differences in the degree of executive involvement (Rende, Ramsberger, & Miyake, 2002; Abrahams, Leigh, Harvey, Vythelingum, Grise, & Goldstein, 2000). Rende et al. (2002), for example, demonstrated that working memory's slave systems are differentially involved in letter and category fluency. More precisely, the

Phonological Loop seems to be involved in letter fluency, whereas the Visuospatial Sketch Pad seems to play an important role in category fluency. Given the compound nature of verbal fluency, it thus seems more useful to define the involved cognitive processes at the level of the different variants of the task (e.g. letter fluency or category fluency), rather than at the level of verbal fluency in general.

This theoretical background shows that verbal fluency is potentially useful to investigate the executive demands of the one-back delaying of a choice reaction. If the requirement to delay a choice reaction one-back interferes with an executively controlled concurrent task such as verbal fluency, it may be predicted that the one-back choice RT task, compared to the choice RT task, will cause more interference with verbal fluency. Furthermore, we know that letter fluency requires additional verbal processing while category fluency also involves visuospatial processing (Rende et al., 2002). Hence, if the executive nature of updating is pure in the sense that neither verbal nor visuospatial processing is measurably involved, it is predicted that the one-back choice RT task will not differentially affect letter and category fluency.

METHOD

Participants and Design. Twenty-four first-year students, enrolled at the Faculty of Psychology and Educational Sciences of Ghent University (Belgium) participated for course requirements and credit. The participants were randomly assigned to one of two groups. The design was a 2 (Group: choice RT task or one-back choice RT task) x 2 (Condition: single-task and dual-task) x 2 (Fluency Task: letter and category fluency) mixed design with repeated measures on the last two factors.

Materials and Procedure . Letter and category fluency tasks were used. A letter fluency task requires participants to produce nouns or verbs beginning with a specified letter. Category fluency requires the participants to generate as many items as possible from a specified category (e.g. animals). In the present experiment, 14 fluency tasks were used: 8 letter fluency (4 nouns with N, A, K, B; 4 verbs with V, D, T, K) and 6 category (flowers, fruits, animals, articles of clothing, names for girls, names for boys) fluency tasks.

The RT tasks used two different and easily discriminable tones with a frequency of 262 (C1 note) and 524 Hz (C1 plus one octave). Each tone lasted 200 msec. The Inter-Stimulus Interval was fixed at 2000 msec. The participants were required to hit the 'one' key or the 'four' key on the numeric pad as fast as possible after they heard a low or a high frequency tone, respectively. They were instructed to rest the index finger of their right hand on the 'one' key and their middle finger on the 'four' key to avoid target seeking movements between both keys. In the one-back choice RT tasks, they were required to delay their response until the next stimulus occurred.

The participants were seated at an 80486 PC with a 15-inch color monitor. The instructions were presented on the computer screen. Prior to the counterbalanced conditions, participants practiced both RT tasks until they met a criterion of 20 consecutively correct (1-back) choice reactions. Next, they performed the 14 verbal fluency tasks: 7 under single-task and 7 concurrently with either simple or choice reaction, depending on which condition they were assigned to. The tasks were counterbalanced over the conditions contrasting single and dual-task verbal fluency performance and with the two kinds of verbal fluency represented equally in both conditions. In other words, the 7 tasks under control and the 7 tasks concurrently executed with either one-back or standard choice reactions, consisted of 4 letter (2 nouns and 2 verbs) and 3 category fluency tasks that were counterbalanced. Half of the participants started with the single-task verbal fluency tasks, the other half with the dual-task conditions.

The cue for the fluency task was centered on the computer screen. 2000 milliseconds later, the word 'START' flickered on the screen to signal the beginning of the verbal fluency task. At this point, the participants generated as many verbal items as possible within 45 seconds. The words were taped by means of an audio recorder. The end of the fluency task was announced by a 100 Hz tone.

In the dual-task conditions, the one-back or standard choice reaction time tasks were started 5000 msec before the fluency task. After this single-task period, the task and the start-signal were presented following the same procedure, and from this point, both tasks were performed concurrently until the final sound. Each participant also performed both RT tasks in a single-task condition for a period of 45 sec.

RESULTS

The number of words generated per 45 seconds were subjected to an analysis of variance on the basis of a 2 (Group: choice RT task or one-back choice RT task) x 2 (Condition: single-task and dual-task) x 2 (Fluency Task: letter and category fluency) mixed design. All data reported in this paper were analyzed by means of a repeated measures analysis based on the multivariate general linear model. The average number of words produced per 45 seconds for each condition is displayed in Table 1.

The analysis revealed significant main effects of Condition, $F(1, 22) = 234.52$, $p < .001$, and Fluency Task, $F(1, 22) = 51.96$, $p < .001$, but no significant main effect of Group, $F < 1$. The interaction of Group and Condition, $F(1, 22) = 13.82$, $p < .01$, indicates that the one-back choice RT task affected verbal fluency more severely than the standard choice RT task. The three-way interaction of Group, Condition and Fluency Task was not significant, $F < 1$.

Further planned comparisons revealed that the choice RT task affected both letter fluency, $F(1, 22) = 64.41$, $p < .001$, and category fluency, $F(1, 22) = 21.86$, $p < .001$. Similarly, the one-back choice RT task affected both letter fluency, $F(1, 22) = 171.70$, $p < .001$, and category fluency, $F(1, 22) = 59.34$,

$p < .001$. The interaction Condition x Fluency Task was neither significant in the choice RT task group, $F < 1$, nor in the one-back choice RT task group, $F(1, 22) = 1.76$, $p > .10$, which indicates that the RT tasks similarly affected letter and category fluency.

	Letter Fluency		Category Fluency	
	Single-Task	Dual-Task	Single-Task	Dual-Task
CRT	7.83 (1.17)	4.31 (1.93)	15.08 (4.20)	9.25 (1.91)
CRT-1	8.87 (1.33)	3.12 (1.62)	15.66 (4.19)	6.05 (1.73)

Table 1. The mean number of words produced per 45 seconds as a function of Group (choice RT task and one-back choice RT task), Condition (single and dual-task) and Fluency Task (letter and category fluency). Standard deviations in parentheses. CRT and CRT-1 stand for choice RT task and 1-back choice RT task, respectively.

DISCUSSION

The results showed that a one-back choice RT task caused more interference with the verbal fluency tasks than the choice RT task. Given that verbal fluency tasks require executive control, this result suggests that executive control is also involved in both secondary tasks and even more in the one-back choice RT task than in the standard choice RT task. Moreover, we observed that the additional interference of the one-back choice RT task was comparable for letter and category fluency. According to the theory put forward by Rende et al. (2002), this shows that there is no involvement of the slave systems in the updating process, at least not to a detectable extent. From Experiment 1, we can conclude that one-back delaying of a choice reaction calls on executive control. The subsequent experiments are aimed to consolidate this position and to investigate more directly whether the interference of the one-back task is produced at the level of the working memory slave systems.

EXPERIMENT 2

Experiment 2 used a verbal short-term memory span procedure with forward and backward serial recall instructions in order to further test our position that one-back delaying of a choice reaction requires executive control and to verify whether the predicted interference is mediated by verbal processing. In the verbal span procedure, subjects are presented a string of consonants at a rate of, for example, one consonant per second and they are instructed to memorize the string and to reproduce it afterwards. This short-term memory task is mainly relying on verbal processing at the level of the Phonological Loop. However, when the number of consonants in the string reaches the individual span level or in other words, when it exceeds the number of letters that can be properly maintained by the Phonological Loop, then the Central Executive has to intervene to manage the exceeding of the verbal capacities (Baddeley & Hitch, 1974). Overall, a verbal span procedure is assumed to put high demands on verbal storage and to a more moderate extent also on executive processing (e.g. Engle, Tuholski, Laughlin, & Conway, 1999).

An often used alternative to the regular forward verbal span procedure is to ask the participants to reproduce the string in the reverse order of presentation, which is known as the backward verbal span task. Performance on a backward verbal span task is often found to be worse than on a forward verbal span task, although differences in span measures, variations in the nature of the verbal material as well as practice effects have resulted in similar levels of performance for both directions recall (e.g. Engle et al., 1999; Farrand & Jones, 1996; Szmalec et al., in press). A nowadays predominant view on verbal serial recall states that a backward recall of verbal material involves the same processes and representations as forward recall, but in addition, it requires a directional transformation which taxes executive resources (Ashman & Das, 1980; Case & Globerson, 1974; Elliott, Smith & McCulloch, 1997; Farrand & Jones, 1996; Gathercole, 1999; Gathercole & Pickering, 2000; Groeger, Field, & Hammond, 1999; Jensen & Figueroa, 1975; Lezak, 1995; Schofield & Ashman, 1986; Smyth & Scholey, 1992; Vandierendonck, De Vooght, & Van der Goten, 1998a; 1998b). Early studies (Hinrichs, 1968; Nilsson, Wright, & Murdock, 1979) have demonstrated that this directional transformation in backward verbal serial recall takes place at encoding, provided that the participants know the required direction in advance (e.g. by using a blocked design, like in the current experiment). The additional executive demands are explained by the fact that in backward verbal span, the automaticity of adding the new letter after the penultimately memorized letter is interrupted in order to put the new letter before the penultimate one. With respect to the verbal demands, forward and backward verbal span tasks are known to involve a similar degree of phonological processing (e.g. Engle et al., 1999; Rosen & Engle, 1999).

The logic of Experiment 2 relies on the differential contribution of executive processing and domain-specific (i.e. verbal) processing to forward and backward verbal serial recall, as described in the previous paragraph. More precisely, we know that backward verbal serial recall is more executively demanding than forward verbal serial recall and that both directions of recall involve a similar degree of verbal processing. This evidence suggests that it should be possible to dissociate verbal from executive involvement in an interference task, by investigating the pattern of dual-task impairment that is obtained when this interference task is simultaneously executed with forward and backward verbal serial recall. Following this rationale, Experiment 2 compares the patterns of dual-task impairment of a one-back and a standard choice RT task, relative to the effects of a secondary task that selectively interferes with verbal processing (i.e. articulatory suppression), on forward and backward verbal serial recall. If one-back delaying of a choice reaction involves executive control while it does not require verbal processing, the predictions specified in what follows should prove to be correct. Note that in the present study, the choice RT task is used as an executive control task in order to investigate whether one-back delaying of a choice reaction creates an additional executive load.

We first predict that the executive control task (the choice RT task) will give evidence of a typically executive pattern of interference, which means that it will interfere more severely with the backward than with the forward span task, as observed by Szmalec et al. (in press). Second, if the one-back choice RT task is executively demanding just like the standard choice RT task is, it is predicted that the same pattern of interference will be obtained. Third, given the hypothesis that the one-back choice RT task requires other executive processes apart from response selection, it is predicted that the one-back choice RT task will have a larger detrimental effect than the standard choice RT task. Finally, since the amount of verbal/phonological resources is similar in forward and backward verbal serial recall, articulatory suppression is anticipated to similarly affect both directions of verbal recall.

METHOD

Participants and Design. Fifty-four first-year students enrolled at the Faculty of Psychology and Educational Sciences of Ghent University (Belgium) participated for course requirement and credit. None of them had taken part in one of the other experiments. They were randomly assigned to one of both reproduction instruction conditions (between-subjects: 27 participants in both conditions), in which verbal serial recall was performed in a single-task condition and in concurrent execution with the choice RT task, the one-back choice RT task and with articulatory suppression. These within-subject-conditions, which also included single-task choice RT and one-back choice RT conditions, were counterbalanced according to a randomized Latin square.

Materials and Procedure. The consonants were chosen from 13 groups with low intergroup confusability according to their Dutch pronunciation.

The groups were: (B, D, P, T), (C), (F, S), (G), (H, K), (J), (L), (M, N), (Q), (R), (V, W), (X), (Z). A string of consonants was composed by selecting one letter at random from each group in order to minimize the phonological similarity between the letters. For the RT tasks, the same parameters were used as in Experiment 1.

The participants were seated at an 80486 PC with a 15-inch color monitor. The instructions were presented on the computer screen and the experiment started with a practice session that consisted of two single trials. A trial started with the presentation of a fixation cross (+) in the center of the screen and a sound (1000 Hz). After 500 msec the cross disappeared and after a 2000 msec blank screen, the first consonant was displayed for 1500 msec, followed by a 500 msec blank screen before the next consonant appeared. The sequence ended with a sound (100 Hz) and three exclamation marks ('!!!') which were meant to trigger the reproduction. The participants were instructed to reproduce as many consonants as possible in the correct order. Oral recall was registered by the experimenter. At the end of reproduction, the experimenter started the next trial. After a two-trial practice, a verbal span task followed, which was also meant as a practice and was not included in the counterbalancing scheme. The verbal span task started with a sequence of three consonants and ended with a sequence of eight consonants. Three trials were presented per sequence; each participant performed 18 (6 sequences x 3) trials, regardless of their individual performance. Prior to the counterbalanced conditions, participants also practiced both RT tasks until they met a criterion of 20 consecutively correct (1-back) choice reactions.

After the practice sessions, participants started with the six conditions that were included in the counterbalancing scheme. In the control condition, participants performed the verbal span task alone. In the dual-task conditions, participants had to perform a secondary task (choice RT task, one-back choice RT task or articulatory suppression) during the presentation phase of the memory task but not during retrieval. The secondary tasks started 5000 msec before the primary task began and both primary and secondary tasks ended with the final sound that announced primary task recall. In the articulatory suppression condition, participants were required to continuously repeat aloud the word ‘de’ (Dutch for the). They were instructed and practiced so that the pace was not less than two and not more than three words per second. The experimenter continuously verified that this pace was respected throughout the experiment. The remaining two conditions that were included in the counterbalancing scheme were a single-task choice RT and a single-task one-back choice RT task condition (each for 12 periods of 20 seconds).

RESULTS

As dependent variable for the verbal memory task, we calculated the proportion of consonants recalled in correct relative order. To that end, we used a transformation of Kendall’s rank correlation coefficient Tau, which reflects the proportion of stimuli recalled in correct relative order (see also Szmalec et al., in press). This measure, τ', is obtained as follows:

$$\tau' = \frac{\sin^{-1}(\tau) + \pi/2}{\pi} \times \frac{n_r}{n}$$

where τ' is the Kendall rank correlation between the orders of the presented and the correctly recalled items, n is the number of presented items and n_r is the number of recalled items. This formula yields an index between 0 and 1. Higher values denote many recalled items in correct order. Low values are obtained when the order is strongly violated or when only few items are recalled. Commission errors were rare and were therefore not taken into account. The τ' was subjected to an analysis based on a 2 (Reproduction Instruction: forward and backward) x 4 (Condition: control, articulatory suppression, one-back choice RT task and choice RT task) mixed design.

The main effect of Reproduction Instruction just failed to be statistically reliable, $F(1, 52) = 3.39$, $p < .10$. The main effect of Condition, $F(3, 50) = 98.79$, $p < .001$, and the interaction Reproduction Instruction x Condition interaction, $F(3, 50) = 5.87$, $p < .01$, were significant. The interaction is displayed in Figure 1.

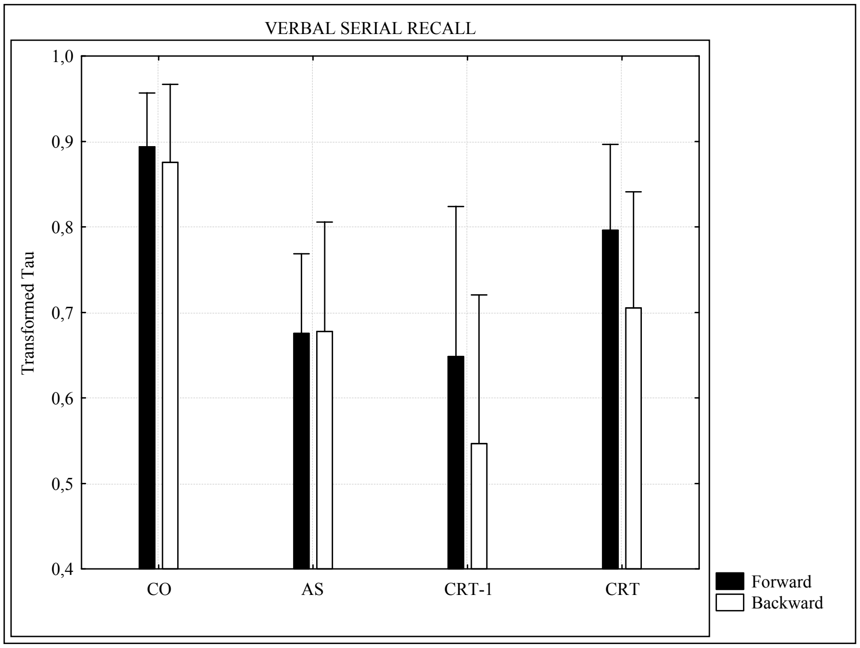

Figure 1. The proportion of consonants recalled in correct relative order (transformed Tau) as a function of the 2 (Reproduction Instruction: forward and backward) x 4 (Condition: control, articulatory suppression, one-back choice RT and choice RT) mixed design (Experiment 2). AS, CRT-1 and CRT stand for articulatory suppression, one-back choice RT task and choice RT task, respectively. Whiskers denote standard errors.

The predictions were tested by means of planned comparisons. These revealed that, under a single-task control condition, performance for forward and backward serial recall of consonants was comparable, $F < 1$. Articulatory suppression affected both forward, $F(1, 52) = 138.86$, $p < .001$, and backward recall, $F(1, 52) = 114.06$, $p < .001$, of consonants. This adverse effect of articulatory suppression was similar in forward and backward recall, $F < 1$. Also the one-back choice RT task affected both forward, $F(1, 52) = 73.97$, $p < .001$, and backward, $F(1, 52) = 132.97$, $p < .001$, verbal recall, but the interference with backward recall was stronger, $F(1, 52) = 4.59$, $p < .05$. The dual-task impairment due to the choice RT task was also larger with backward than with forward recall, $F(1, 52) = 7.82$, $p < .01$. The one-back choice RT task interfered more severely with forward recall, $F(1, 52) = 36.23$, $p < .001$, and with backward recall, $F(1, 52) = 41.78$, $p < .001$, than the choice RT task. The interaction of Reproduction Instruction with the planned contrast between Articulatory Suppression and the one-back Choice RT task was significant, $F(1, 52) = 9.08$, $p < .01$. The interaction of Reproduction Instruction with the contrast between the one-back Choice RT task and the Choice RT task was not significant, $F < 1$.

DISCUSSION

Experiment 2 demonstrated that the one-back choice RT task interfered more with a primary task that involves executive control than the choice RT task. In addition, when the executive demands of the primary task were augmented by reproducing the verbal items in the reverse order of presentation, the interference of the one-back choice RT task increased. Furthermore, Experiment 2 demonstrated that the pattern of dual-task interference of the one-back choice RT task with forward and backward verbal serial recall dissociated from the interference observed with the articulatory suppression, while it ran parallel with the dual-task impairment observed with the executive control task, the standard choice RT task. Altogether, these findings consolidate the position that the one-back choice RT task gives evidence of an executive pattern of interference and that this interference is not produced at the level of the verbal working memory slave system. Given the architecture of working memory as proposed by Baddeley (1986), the one-back choice reaction must be investigated in interaction with visuospatial processing so as to assess its relation to the Visuospatial Sketch

Pad. This is the logical and imperative next step in determining the working memory demands of the one-back choice reaction task.

EXPERIMENT 3

Experiment 3 was designed to consolidate the position that a one-back choice RT task produces an executive pattern of dual-task interference and to test whether the interference, as it is not produced at the level of the Phonological Loop (Experiment 2), is neither due to a visuospatial involvement. To this end, we used the visuospatial counterpart to the verbal span task, namely the Corsi blocks task (for a review on the Corsi blocks task, see Berch, Krikorian, & Huha, 1998). In the Corsi blocks task, the experimenter points to a number of blocks (1 up to 9) that are irregularly positioned on a board. After presentation of the block-sequence, the participants are required to reproduce it in the same serial order as it was presented by the experimenter. Analogous to the verbal domain, an often used variation on the forward Corsi blocks task is to ask the participants to reproduce the spatial items in the reverse order of presentation, a procedure which has been shown to yield a similar level of performance as the forward Corsi blocks task (Isaacs & Vargha-Khadem, 1989; Szmalec et al., in press; Vandierendonck et al., 2004; Wilde & Strauss, 2002). For many years, the Corsi blocks task has been used to measure visuospatial short-term memory performance, both in healthy and clinical groups.

Regarding the working memory components involved in the Corsi blocks task, a number of selective interference studies (Vandierendonck, Kemps, Fastame, & Szmalec, 2004; Szmalec et al., in press; Vecchi & Richardson, 2001) demonstrated that both visuospatial and executive resources are required. With respect to the visuospatial involvement, the findings are slightly different from what is found with articulatory suppression in the verbal domain. More precisely, performance is more impaired by a secondary task which interferes with spatial rehearsal in the forward than in the backward direction of visuospatial serial recall (Szmalec et al., in press; Vandierendonck et al., 2004). This finding which could be taken to mean that the Visuospatial Sketch Pad is more involved in the forward than in the backward Corsi blocks task, receives support from recent neuropsychological evidence (Mammarella, Cornoldi, & Donadello, 2003). This specific issue has been addressed more directly in a recent study by Vandierendonck and Szmalec (in press). Based on Wheeler and Treisman's (2002) binding theory for visual short-term memory, Vandierendonck and Szmalec (in press) argued that performance for the backward memorization of block-sequences benefits from a recency effect in the sense that the last three to four blocks can be recalled without spatial rehearsal. This might explain why matrix tapping, a task that is known to interfere with visuospatial rehearsal (e.g. Logie, 1995), interferes less with the backward version of the Corsi blocks task.

Another characteristic of spatial serial recall is that no additional executive resources are required to reverse the order of the items (Smyth & Scholey, 1992). Smyth and Scholey explain this by the fact that series of spatial items are encoded in visuospatial patterns, both in forward and backward recall, with no involvement of serial order. Accordingly, whereas executive resources are required to reverse the order in verbal serial recall, the reversal in spatial serial recall is not executively demanding. This position is supported by the observation that an executive secondary task similarly affects the encoding of forward and backward Corsi block sequences (Szmalec et al., in press; Vandierendonck et al., 2004).

By analogy with Experiment 2, the logic of Experiment 3 relies on the differential involvement of domain-specific (visuospatial) processing and the comparable involvement of executive processing in backward and forward recall of Corsi blocks. Based on this logic, it can be anticipated that executive and visuospatial secondary tasks will dissociate in terms of their interaction with the direction of recall in the Corsi blocks task (as demonstrated by Vandierendonck et al., 2004). Hence, the purpose of this experiment is to investigate whether the one-back choice RT task gives evidence of an executive pattern of interference and whether this pattern dissociates from the dual-task impairment observed with matrix tapping.

If the choice RT task interferes with a spatial task demanding executive control while this interference is not produced at the level of the Visuospatial Sketch Pad, the following predictions can be formulated. First, given that the Corsi blocks task requires executive control, it is predicted that the one-back choice RT task will impair the Corsi block task to a larger extent than the standard choice RT task. Second, knowing that the executive demands of the forward and backward variants of the Corsi blocks task are the same, we expect that the presumed executive one-back choice RT task will similarly affect forward and backward recall of visuospatial positions, just like the executive control task (i.e. the choice RT task). Finally, given the differential contribution of visuospatial processing to the forward and backward Corsi task, we predict that the contrast between the one-back choice RT task and a task that selectively interferes with visuospatial processing (i.e. matrix tapping; Farmer, Berman, & Fletcher, 1986) will interact with direction of recall.

METHOD

Participants and Design. Forty-six first-year students enrolled at the Faculty of Psychology and Educational Sciences of Ghent University (Belgium) participated for course requirement and credit. None of them participated in one of both other experiments. They were randomly assigned to one of both reproduction instruction conditions (between-subjects: 23 participants in both conditions), in which the Corsi block tapping task was performed in a single-task condition and in concurrent execution with the choice RT task, the one-back choice RT task and with matrix tapping. These within-subject conditions, which also included single-task choice RT, one-back choice RT and matrix tapping conditions, were counterbalanced according to a randomized Latin square.

Materials and Procedure**.** A computerized version of the Corsi blocks task was presented on a 15-inch color touch screen (80486 PC). The 9 blocks were 30 x 30 mm white squares, positioned on a blue background according to Corsi's (1972) original configuration. The presentation of a block-sequence was monitored by the computer: each block in turn was highlighted by changing its color from white to black for 1 s, with an inter-block interval of 0.5 s.

The start of presentation was announced by a 400 msec 1000 Hz sound. The presentation ended with a 400 msec 100 Hz sound, which announced the reproduction phase. The participants were instructed to reproduce the highlighted blocks by touching the squares on the screen in the same or reverse order of presentation, depending on the condition they were assigned to. When a square was touched by the participant, it turned black for 200 msec in order to provide feedback on the touching operation. At the end of recall, the participant was required to hit the escape key and after a 2s inter-trial interval, the next trial started. A condition started with a sequence of three and ended with a sequence of eight blocks. Three trials were presented at each sequence length, so each condition contained 18 trials.

Instructions were presented on the computer screen. Prior to the counterbalanced conditions, participants performed two practice trials and an entire single-task Corsi practice block. Next, they practiced both RT tasks until they met a criterion of 20 consecutively correct (1-back) choice reactions. Then, the seven counterbalanced conditions followed. In the control condition, participants performed the Corsi block-tapping task alone. In the dual-task conditions, the secondary tasks (matrix tapping, the choice RT task and the one-back choice RT task) were executed during the presentation of the Corsi block sequences but not during retrieval. Matrix tapping required the participants to hit the four corners of the numeric keypad in counterclockwise order at a pace of 2-3 keys per second. This operation was registered in terms of accuracy and latency. The other secondary tasks were the same RT tasks as in the previous experiments. Performance on the three secondary tasks was also registered in a single-task situation (each task for 12 periods of 20 seconds).

RESULTS

We used the same dependent variable as in Experiment 2, namely the proportion of spatial positions recalled in correct relative order, based on the transformed Tau (τ') formula. This measure was entered as the dependent variable in a 2 (Reproduction Instruction: forward and backward) x 4 (Condition: control, matrix tapping, choice RT and simple RT) mixed design.

The main effect of Reproduction Instruction was not significant, $F(1, 44) = 1.08$, $p > .10$, while the main effect of Condition, $F(3, 42) = 53.51$, $p < .001$, and the interaction of Reproduction Instruction and Condition, $F(3, 42) = 4.38$, $p < .01$, were significant. Figure 2 displays the interaction.

Planned comparisons showed that, in the single-task control condition, performance was comparable for both forward and backward serial recall of Corsi blocks, $F < 1$. Matrix tapping affected both forward, $F(1, 44) = 56.13$, $p < .001$, and backward, $F(1, 44) = 7.25$, $p < .01$, recall of block sequences but the interference was significantly stronger for forward than for backward recall, $F(1, 44) = 11.52$, $p < .01$. The one-back choice RT task interfered with forward, $F(1, 44) = 56.78$, $p < .001$, and backward, $F(1, 44) = 60.42$, $p < .001$, recall of Corsi block sequences. The degree of interference was comparable for both reproduction instruction conditions, $F < 1$. Also the choice RT task similarly affected forward and backward recall of Corsi block sequences, $F < 1$. The one-back choice RT task was more impairing than the choice RT task on both forward recall, $F(1, 44) = 38.44$, $p < .001$, and backward recall, $F(1, 44) = 36.10$, $p < .001$. Finally, the interaction of

Reproduction Instruction with the contrast between Matrix Tapping and the one-back Choice RT task was significant, $F(1, 44) = 5.31$, $p < .05$, while the interaction of Reproduction Instruction with the contrast between the one-back Choice RT task and the Choice RT task was not, $F < 1$.

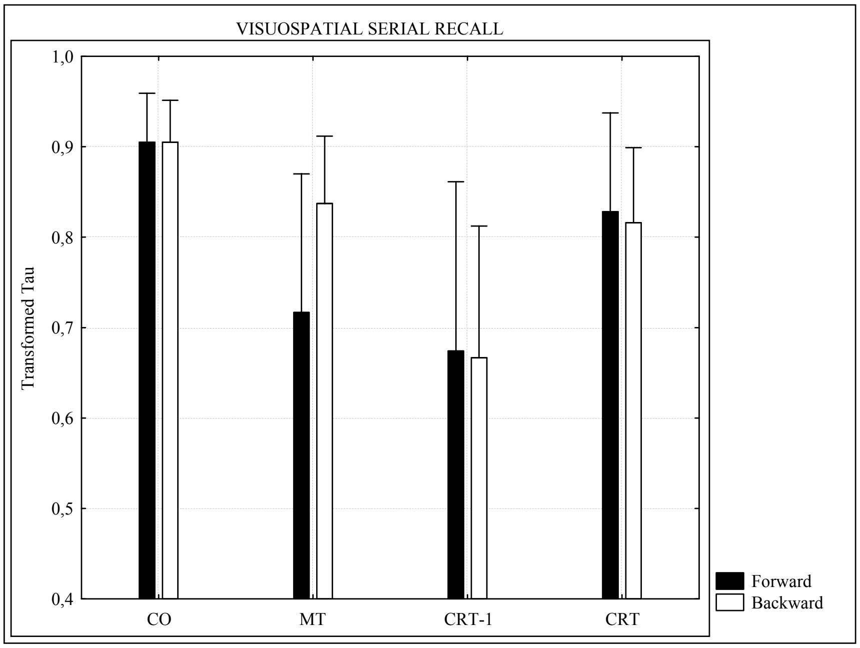

Figure 2. The proportion of blocks recalled in correct relative order (transformed Tau) as a function of the 2 (Reproduction Instruction: forward and backward) x 4 (Condition: control, matrix tapping, one-back choice RT and choice RT) mixed design (Experiment 3). MT, CRT-1 and CRT stand for matrix tapping, one-back choice RT task and choice RT task, respectively. Whiskers denote standard errors.

DISCUSSION

The data from Experiment 3 demonstrated that the one-back choice RT task was more impairing on the Corsi blocks task than the choice RT task, which implies that the one-back delaying process caused additional interference with primary tasks that involve executive control. Furthermore, we observed a dissociation between the matrix tapping and the one-back choice RT task interference in the comparison of forward and backward recall conditions. More precisely, while the one-back choice RT task interfered with forward and backward recall to the same extent, matrix tapping had a stronger adverse effect on forward than on backward recall. This dissociation supports a qualitative differentiation between the cognitive processes that underlie performance on both tasks. Based on these findings, we argue that the dual-task effects of the one-back choice reaction are not produced at the level of the Visuospatial Sketch Pad. Given the typical executive pattern of interference with the forward and backward variants of the Corsi blocks task elicited by the one-back choice RT task (Szmalec et al., in press; Vandierendonck et al., 2004), also Experiment 3 supports the thesis that the interference occurs at the level of the Central Executive instead.

ANALYSES OF RT TASK PERFORMANCE

Further analyses were performed to specify the extent to which the RT tasks were affected by the concurrent execution of verbal and visuospatial serial recall and verbal fluency. Such analyses are necessary to investigate whether no dual-task tradeoffs occurred in the sense that the additional interference of the one-back choice RT task might be explained by a smaller dual-task cost (i.e. better performance in dual-task setting) for the one-back choice RT task compared to the choice RT task. Because the RT task performance analyses yielded a similar pattern of results in all three experiments, we decided to pool the three data sets.

Speed (mean reaction times) and accuracy data (mean percentages of choice reaction mistakes) for the choice RT tasks are displayed in Table 2. With respect to the reaction times, these data show that in a single-task condition the one-back choice RT task was performed faster than the standard choice RT task, $F(1, 111) = 14.86$, $p < .001$. Furthermore, both the standard and the one-back choice RT task were affected under dual-task conditions: $F(1, 111)$

= 186.83, $p < .001$ and $F(1, 111) = 211.86$, $p < .001$, respectively. The interaction of the standard vs. the one-back choice RT task contrast and the single-task vs. dual-task contrast was not significant, $F < 1$. This shows that the dual-task costs of both RT tasks were comparable. Because the distribution of the accuracy data does not meet the ANOVA assumptions, we used a nonparametric sign test for dependent samples to compare the accuracy on both RT tasks. The results show that the one-back choice RT task was performed as accurately as the standard choice RT task, both under single as under dual-task conditions (both p's > .10).

	Speed		Accuracy	
	Single-Task	Dual-Task	Single-Task	Dual-Task
CRT	509 (83)	662 (122)	1.82 (2.01)	5.95 (6.37)
CRT-1	464 (121)	612 (149)	2.71 (3.71)	6.90 (6.42)

Table 2. Mean speed (reaction times) and accuracy data (percentage of choice reaction mistakes) for the RT tasks as a function of Task (choice RT task and one-back choice RT task) and Condition (single and dual-task), averaged over Experiments 1, 2 and 3. Standard deviations in parentheses. CRT and CRT-1 stand for choice RT task and 1-back choice RT task, respectively.

Finally, we analyzed the percentage of anticipatory reactions that were made in the RT tasks. In the standard choice RT task, anticipations were rare. In the one-back choice RT task, on average 1.83 (SD = 4.66) percent anticipations were made under single-task and 2.93 (SD = 3.84) percent under dual-task conditions. A nonparametric sign test revealed that this dual-task cost was significant ($p < .001$).

GENERAL DISCUSSION

The purpose of this study was to investigate the executive demands of a one-back choice reaction by means of the selective interference paradigm. We predicted that a one-back choice RT task would interfere with other tasks calling on executive control, based on the theoretical position that a one-back choice RT task bears strong resemblance to the *n*-back updating procedure described by Morris and Jones (1990). A series of experiments was designed in order to compare the patterns of dual-task interference of a one-back and a standard choice RT task in simultaneous execution with executive, verbal and visuospatial primary tasks. By comparing the interference of both RT tasks with letter and category fluency, Experiment 1 demonstrated that the one-back task interfered more with verbal fluency than a standard choice RT task. Experiments 2 and 3 were designed to demonstrate that the basis of the augmented interference observed in Experiment 1 is executive in nature and is not produced at the level of working memory's verbal or visuospatial slave systems. Experiment 2 showed that in concurrent execution with forward and backward verbal serial recall, the one-back choice RT task gave evidence of a typical executive pattern of interference and that the one-back choice RT task was qualitatively dissociable from a verbal secondary task. In the same vein, Experiment 3 showed that in simultaneous execution with forward and backward visuospatial serial recall, the pattern of selective interference of the one-back choice RT task was typical for an executive task. Moreover, it was qualitatively separable from the pattern produced by a task that requires visuospatial processing. Overall, these results show that the one-back delaying of a choice reaction interferes with tasks calling on executive control and that neither verbal nor visuospatial processing is involved in this task, at least not to a measurable extent. Therefore, it is concluded that a one-back choice reaction puts larger demands on executive control than a standard choice reaction.

Morris and Jones (1990) demonstrated that their *n*-back procedure also involves non-executive working memory processes which are related to the modality of the material that must be updated. In their task, letter strings had to be maintained and updated, which explains why also the Phonological Loop is involved. The present findings show that the one-back choice RT task is a source of executive interference with no measurable involvement of verbal or visuospatial processing. This raises the question how participants store the auditory signals in a one-back choice RT task in order to bridge the delay period. One possibility is to verbally recode the stimuli (high or low) and hold this verbal representation during the delay by verbal rehearsal. However, this would induce a continuous verbal load in the one-back task ─ something similar to an articulatory suppression ─ and this in addition to the executive demands of the task, offers an explanation that does not fit well within the observed patterns of interference with verbal serial recall; the same goes for an explanation in terms of spatial recoding. It is certainly not excluded that, in addition to the executive demands, minor verbal or visuospatial involvement might elude our measuring procedure but this can hardly be the case for a presumed verbal involvement which should be responsible for rehearsing phonological information (i.e. high or low) throughout the entire inter-stimulus interval. If the one-back delay period is not bridged by appealing to the slave systems, how is the task-relevant information maintained then? An answer to this question might be provided by findings from the motor preparation literature (e.g. Toni, Thoenissen & Zilles, 2001). Motor preparation is often measured by a delayed responding paradigm. A delayed RT task, for example, differs from a one-back task in the fact that in a delayed RT task, the response is triggered by an arbitrary signal before the next stimulus, which implies that the moment the next stimulus is presented, there is no active maintenance and by consequence no content to update. Toni et al. (2001) argued that in a delayed choice reaction procedure, provided that the motor response can be prepared in advance, the motor response itself is used to bridge the delay period, and they demonstrated that the representation of this motor response is dissociated from working memory processes (see also Toni, Thoenissen, Zilles, & Niedeggen, 2002). Conversely, when participants are obliged to store the stimulus during the delay period, either by experimental manipulation (e.g. Toni et al., 2001) or by the nature of the task itself (e.g. storing consonants), working memory is required. According to the theory put forward by Toni et al. (2001), a one-back choice RT procedure like the present one allows motor preparation, which might explain why no working memory storage was measured during the delay period. Interestingly, this idea matches the subjective impressions described by the participants to the present experiments. They consistently reported performing the one-back choice RT task by preparing the motor response, holding it standby until the next stimulus and then, finishing with the execution. This seems to suggest that in a one-back choice RT task, and perhaps also in the Morris and Jones (1990) *n*-back procedure, it is particularly the requirement to keep a task-set representation active and to update this representation which is executively demanding, independently of the nature of the representation.

Some years ago, Smith and Jonides (1997) suggested that one-back might be a special case of the *n*-back task in the sense that it does not involve updating. Smith and Jonides (1997) investigated the neural basis of working memory by means of PET and therefore, they used an *n*-back task with parametric variations of n going from 0 up to 3. They observed that the number of activated brain regions increased with n but, it was especially as from n = 2 that the Dorsolateral Prefrontal Cortex (DPFC) became involved in the task. Since DPFC has often been associated with executive functions (e.g. D'Esposito, Detre, Alsop, Shin, Atlas, & Grossman, 1995), Smith and Jonides provided an indirect argument against executive involvement in a one-back task. This argument was in turn weakened by the more recent findings of Van der Linden et al. (1999) who demonstrated that the Frontopolar cortex mediates the process of updating, while DPFC is more likely to serve a storage function in working memory. Our findings strongly suggest that executive control is involved in a one-back task and, as far as the updating process is the locus of executive control in the one-back choice RT task, it seems that updating is involved in a one-back task.

As described in the introduction, we do not take for granted that only the updating process qualifies for the additional executive involvement that is measured in a one-back choice RT task compared to a standard choice RT task. In what follows, we present two alternative explanations which challenge the notion of updating as the locus of executive control in the one-back task. The first is grounded in the recent developments demonstrating that also a choice RT task involves executive control (Allain et al., 2004; Rowe et al., 2000; Szmalec et al., in press). In a sense, the current findings demonstrate that a temporal manipulation (i.e. the delaying) of the choice reaction process affects the executive demands of a choice RT task. One cannot exclude that it might also be the active maintenance - which is required to bridge the delay period - that involves executive control and not (only) the updating process. The position that specifically the updating phase itself is executively demanding, as opposed to thinking of the active maintenance for example, has only been supported indirectly (e.g. Morris & Jones, 1990). It is not unthinkable that the additional executive demands of the one-back choice RT task are due to the fact that the same executive process activated to supervise the correct response selection in a choice RT task is also activated in a one-back choice RT task but to a temporarily different extent (i.e. as a function of the length of the delay period). This idea is based on Allain et al.'s (2004) electromyographic study which demonstrated that the executive demands of a choice RT task can be attributed to the fact that participants exert an online executive control that supervises the RT task until the motor execution of the response is terminated. Our point is that it cannot be excluded that in a one-back delayed choice RT task, this online control is prolonged as a function of the delay period, which might also explain the additional executive demands of a one-back choice RT task. It is important to further investigate whether the executive demands of a one-back RT task differ from the executive demands of a regular RT task (1) in terms of a qualitatively different process (i.e.

updating) or (2) in quantitative (i.e. temporal) terms or (3) maybe both. This would be crucial information for the scientific debate on the unity and diversity in executive control (see Miyake et al., 2000). What the present study contributes to this debate is the idea that the findings regarding the additional executive demands of a one-back choice RT task compared to a choice RT task can be theoretically framed without invoking a qualitatively different process.

Another alternative explanation for the increased executive demands of the one-back choice RT task is related to the fact that during a one-back choice reaction, there is an overlap of successive trials. In a one-back choice RT task, where the occurrence of stimulus x triggers the reaction on stimulus x-1, the cognitive processing of stimulus x should be commenced before the choice reaction on stimulus x-1 is completed. If this were not the case, no relevant information on stimulus x would be available when the response on stimulus x-1 is terminated and hence, it would simply not be possible to go on with the task. It is not excluded that this partial temporal overlap between the choice reactions on stimulus x-1 and on stimulus x induces a competition between the task sets for those stimuli and that executive control is required to prevent that interference occurs at that level. Further research which directly addresses this issue would be welcome.

Finally, what are the implications of the present study for executive function research in general? In our view, the selective interference paradigm is a powerful paradigm to study executive control. It offers a framework to design interference tasks that operationalize presumed executive processes and to test whether these processes are under executive control. Then, the changes in executive involvement associated with further parametric manipulations on these interference tasks (like the one-back manipulation in this study) can improve our understanding of presumed executive processes and can contribute to a clarification of the ill-defined concept of executive control. In addition, the interference tasks themselves can be useful to those working memory studies aimed to investigate the overall executive involvement or the involvement of a particular executive process in more complex cognitive activities such as mental arithmetic, for example (e.g. Deschuyteneer & Vandierendock, in press; Deschuyteneer, Vandierendonck, & Muyllaert, submitted).

REFERENCES

Abrahams, S., Leigh, P.N., Harvey, A., Vythelingum, G.N., Grise, D., & Goldstein, L.H. (2000). Verbal fluency and executive dysfunction in Amyotrophic Lateral Sclerosis (Als). *Neuropsychologia, 38*, 734-747.

Allain, S., Carbonnell, L., Burle, B., Hasbroucq, T., & Vidal, F. (2004). On-line executive control: An electromyographic study. *Psychophysiology, 41*, 113-116.

Ashman, A. F., & Das, J. P. (1980). Relation between planning and simultaneous-successive processing. *Perceptual and Motor Skills, 51*, 371-382.

Baddeley, A. D. (1986). *Working Memory*. Oxford: Oxford University Press, Clarendon Press.

Baddeley, A. (1996). Exploring the Central Executive. *Quarterly Journal of Experimental Psychology, 49A*, 5-28.

Baddeley, A. (2000). The Episodic Buffer: A new component of Working Memory? *Trends in Cognitive Sciences, 4*, 417-423.

Baddeley, A., Emslie, H., Kolodny, J., & Duncan, J. (1998). Random generation and the executive control of working memory. *Quarterly Journal of Experimental Psychology, 51A*, 819-852.

Baddeley, A., & Hitch, G. (1974). Working Memory. In G. A. Bower (Ed.), *Recent Advances in Learning and Motivation*. (pp. 47-90). New York: Academic Press.

Baddeley, A., Lewis, V., Eldridge, M., & Thomson, N. (1984). Attention and retrieval from long term memory. *Journal of Experimental Psychology: General, 113*, 518-540.

Barnard, P. J., Scott, S. K., & May, J. (2001). When the Central Executive lets us down: Schemas, attention, and load in a generative working memory task. *Memory, 9*, 209-221.

Berch, D. B., Krikorian, R., & Huha, E. M. (1998). The Corsi block-tapping task: Methodological and theoretical considerations. *Brain and Cognition, 38*, 317-338.

Bunge, S. A., Hazeltine, E., Scanlon, M. D., Rosen, A. C., & Gabrieli, J. D. (2002). Dissociable contributions of prefrontal and parietal cortices to response selection. *Neuroimage, 17*, 1562-71.

Case, R., & Globerson. (1974). Field independence and central computing space. *Child Development, 45*, 772-778.

Denckla, M. (1994). Measurement of executive function. In G. Reid Lyon (Ed.), *Frames of reference for the assessment of learning disabilities. New views on measurement issues*. (pp. 117-142). Baltimore, MD: Paul H. Brookes.

Deschuyteneer, M. & Vandierendonck, A. (in press). Are ‘input monitoring’ and ‘response selection’ involved in solving simple mental arithmetical sums? *European Journal of Cognitive Psychology.*

Deschuyteneer, M., Vandierendonck, A., & Muyllaert, I. (submitted). Is ‘memory updating’ involved in solving simple mental arithmetic sums and products? *Manuscript submitted for publication.*

D’Esposito, Detre, Alsop, Shin, Atlas, & Grossman. (1995). The neural basis of the central executive of working memory. *Nature, 378*, 279-281.

Elliot, C.D., Smith, P., & McCulloch, K. (1997). British Ability Scales II. Technical Manual. Windsor, UK: NFER-Nelson.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128*, 309-331.

Farmer, E.W., Berman, J.V.F., & Fletcher, Y.L. (1986). Evidence for a visuospatial scratch-pad in working memory. *Quarterly Journal of Experimental Psychology , 38A*, 675-688.

Farrand, P., & Jones, D. (1996). Direction of report in spatial and verbal serial short-term memory. *Quarterly Journal of Experimental, 49A*, 140-158.

Frith, C. D., & Done, D. J. (1986). Routes to action in reaction-time tasks. *Psychological Research-Psychologische Forschung, 48*, 169-177.

Gathercole, S. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Science, 3*, 410-418.

Gathercole, S., & Pickering, S. J. (2000). Working memory deficits in children with low achievements in the national curriculum at 7 years of age. *Britisch Journal of Educational Psyhology, 70*, 177-194.

Groeger, J. A., Field, D., & Hammond, S. M. (1999). Measuring memory span. *International Journal of Psychology, 34*, 359-363.

Hegarty, M., Shah, P., & Miyake, A. (2000). Constraints on using the dual-task methodology to specify the degree of central executive involvement in cognitive tasks. *Memory & Cognition, 28*, 376-385.

Hinrichs, J.V.(1968). Prestimulus and poststimulus cueing of recall order in the memory span. *Psychonomic Science, 12*, 261 - 262.

Isaacs, E.B., & Vargha-Khadem, F. (1989). Differential course of development of spatial and verbal memory span : A normative study. *Britisch Journal of Developmental Psychology, 7*, 377-380.

Jensen, A. R., & Figueroa, R. A. (1975). Forward and backward digit span interaction with race and IQ - Predictions from Jensens theory. *Journal of Educational Psychology, 67*, 882-893.

Klauer, K. C., & Stegmaier, R. (1997). Interference in immediate spatial memory: shifts of spatial attention or central-executive involvement? *Quarterly Journal of Experimental Psychology, 50A*, 79-99.

Lezak, M. D. (1995). *Neuropsychological assessment*. New York: Oxford University Press.

Logie, R. H. (1995). *Visuo-spatial working memory*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Mammarella, N., Cornoldi, C., Donadello, E. (2003). Visual but not spatial working memory deficit in children with spina bifida. *Brain and Cognition, 53*, 311-314.

Martin, A., Wiggs, C.L., Lalonde, F., & Mack, C. (1994). Word retrieval to letter and semantic cues - a double dissociation in normal subjects using interference tasks. *Neuropsychologia, 32*, 1487-1494.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49-100.

Morris, N., & Jones, D. M. (1990). Memory updating in working memory: The role of the central executive. *British Journal of Psychology, 81*, 111-121.

Nilsson, L.G., Wright,E., & Murdock,B.B. (1979). Order of recall, output interference, and the modality effect. *Psychological Research, 41*, 63-78.

Parker, D. M., & Crawford, J. R. (1992). Assessment of frontal lobe dysfunction. In J.R. Crawford, D. M. Parker, & W. M. McKinlay (Eds.), *A handbook of neuropsychological assessment*. (pp. 267-291). Hove: Lawrence Erlbaum Associates Ltd.

Phillips, L. H. (1997). Do "frontal tests" measure executive function?: Issues of assessment and evidence from fluency tests. In P. Rabbitt (Ed.), *Methodology of Frontal and Executive Function*. (pp. 191-214). Hove, UK: Psychology Press.

Pollack, I., Johnson, L., & Knaft, P. (1959). Running memory span. *Journal of Experimental Psychology, 57*, 137-146.

Rabbitt, P. (1997). *Methodology of frontal and executive function*. Hove, UK: Psychology Press.

Reitan, R. M., & Wolfson, D. (1994). A selective and critical-review of neuropsychological deficits and the frontal lobes. *Neuropsychology Review, 4*, 161-198.

Rende, B., Ramsberger, G., & Miyake, A. (2002). Commonalities and differences in the working memory components underlying letter and category fluency tasks: A dual-task investigation. *Neuropsychology, 16*, 309-321.

Rosen, V.M., & Engle, R.W. (1997). Forward and Backward Serial Recall. *Intelligence, 25*, 37-47.

Rowe, J. B., Toni, I., Josephs, O., Frackowiak, R. S. J., & Passingham, R. E. (2000). The prefrontal cortex: Response selection or maintenance within working memory? *Science, 288*, 1656-1660.

Schofield, N. J., & Ashman, A. F. (1986). The relationship between digit span and cognitive processing across ability groups. *Intelligence, 10*, 59-73.

Schubert, T. (1999). Processing differences between simple and choice reactions affect bottleneck localization in overlapping tasks. *Journal of Experimental Psychology-Human Perception and Performance, 25*, 408-425.

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology, 33*, 5-42.

Smith, E. E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science, 283*, 1657-1661.

Smith-Spark, J. H., Fisk, J. E., Fawcett, A. J., & Nicolson, R. I. (2003). Investigating the central executive in adult dyslexics: Evidence from phonological and visuospatial working memory performance. *European Journal of Cognitive Psychology, 15*, 567-587.

Smyth, M. M., & Scholey, K. A. (1992). Determining spatial span - the role of movement time and articulation rate. *Quarterly Journal of Experimental Psychology, 45A*, 479-501.

Szmalec, A., Vandierendonck, A., Kemps, E. (in press). Response selection involves executive control: Evidence from the selective interference paradigm. *Memory & Cognition*.

Toni, I., Thoenissen, D., & Zilles, K. (2001). Movement preparation and motor intention. *Neuroimage, 14*, S110-S117.

Toni, I., Thoenissen, D., Zilles, K., & Niedeggen, M. (2002). Movement preparation and working memory: A behavioural dissociation. *Experimental Brain Research, 142*, 158-162.

Van der Linden, M., Collette, F., Salmon, E., Delfiore, G., Degueldre, C., Luxen, A., & Franck, G. (1999). The neural correlates of updating information in verbal working memory. *Memory, 7*, 549-560.

Vandierendonck, A., De Vooght, G., & Van Der Goten, K. (1998a). Interfering with the Central Executive by means of a Random Interval Repetition task. *Quarterly Journal of Experimental Psychology, 51A*, 197-218.

Vandierendonck, A., De Vooght, G., & Van Der Goten, K. (1998b). Does random time interval generation interfere with working memory executive functions? *European Journal of Cognitive Psychology, 10*, 413-442.

Vandierendonck, A., Kemps, E., Fastame, M.C., & Szmalec, A. (2004). Working memory components of the Corsi blocks task. *British Journal of Psychology, 95*, 57-79.

Vandierendonck, A., & Szmalec, A. (in press). An asymmetry in the visuospatial demands of forward and backward recall in the Corsi blocks task. *Imagination, Cognition and Personality*.

Vecchi, T., & Richardson, J.T.E. (2001). Measures of visuospatial short-term memory: The Knox cube imitation test and the Corsi blocks test compared. *Brain and Cognition, 46*, 291-294.

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General, 131*, 48-64.

Wilde, N., & Strauss, E. (2002). Functional Equivalence of Wais-Iii/Wms-Iii Digit and Spatial Span Under Forward and Backward Recall Conditions. *Clinical Neuropsychologist, 16*, 322-330.

CHAPTER 4
THE AMOUNT OF EXECUTIVE CONTROL INVOLVED IN A CHOICE RT TASK AS A FUNCTION OF RESPONSE CONFLICT

***Manuscript under revision*[1]**

An increasing number of studies demonstrated that executive control is involved in a choice RT task. Based on the perceptual overlap/response conflict theory put forward by Nieuwenhuis, Yeung and Cohen (2004), the present Event Related brain Potential (ERP) study used the N2 as an electrophysiological marker of executive control in order to test the hypothesis that the amount of executive control involved in a choice RT task is a function of the degree of response conflict, as induced by the level of perceptual overlap among the stimuli. To this end, an experiment was designed in which 13 participants performed a simple and a choice RT task under three different levels of stimulus discriminability. The data revealed that the N2 observed in the ERPs associated with the choice RT task was amplified with increasing perceptual overlap, while no N2 component was observed in the simple RT task conditions. It is concluded that the executive demands of a choice RT task depend on the level of response conflict which is determined by the perceptual overlap between stimuli. In the discussion, the present conclusion is integrated into current theoretical accounts of executive involvement in choice reaction.

---

[1] This paper was co-authored by Frederick Verbruggen, Wouter De Baene and André Vandierendonck

INTRODUCTION

In research on executive control, often postulated executive processes such as inhibition or task switching have since long been measured by several variants of choice RT tasks, like the Go/Nogo task, conflict tasks such as the Stroop task or switching between choice RT tasks. In the mean time, both behavioral and electromyographic (EMG) studies have provided empirical support for the position that executive control is also involved in a speeded choice RT task where participants are only required to make a binary choice reaction based on a compatible (e.g. left pointing arrow = left) or neutral (e.g. circle = left) stimulus-response mapping (Allain, Carbonnell, Burle, Hasbroucq, & Vidal, 2004; Klauer & Stegmaier, 1997; Szmalec, Vandierendonck, & Kemps, in press). Whereas there is relative consensus about the sources of executive involvement in more complex variants of choice RT tasks like the Stroop task or the Go/Nogo task, it is at the moment less clear which central processing demands (or which so-called executive function(s)) are responsible for the cognitive control exerted in the basic variants of the choice RT task.

Recently, Carbonnell, Hasbroucq, Grapperon and Vidal (2004) observed EMG and electrophysiological markers of inhibition in a binary choice RT task, which indicate that response inhibition is involved in a choice reaction in order to suppress the activation of the incorrect response, so that the correct response can be executed (see also Burle, Vidal, Tandonnet, & Hasbroucq, in press). If inhibition of incorrect response activation is a source of executive involvement in a choice RT task, it can be assumed that the amount of executive control exerted in a choice RT task is a function of the degree of activation of the erroneous response, or in other words, a function of the degree of response conflict between the activated response alternatives. The present study uses the N2 component of the ERP to test this assumption.

In ERP studies of cognitive control, the N2 is a usually observed negative deflection of the stimulus-locked ERP with a frontocentral topography. It is assumed to be produced by activation of the anterior cingulated cortex (ACC), a brain structure that is believed to play a predominant role in executive or cognitive control (see Botvinick, Cohen, & Carter, 2004, for a review). To date, no consensus was reached on which cognitive processes are reflected by the N2: some researchers argue that it reflects response inhibition (e.g. Falkenstein, Hoormann, & Hohnsbein, 1999; Kok, 1986), while others see it as an index of response conflict (Nieuwenhuis, Yeung, Van den Wildenberg, & Ridderinkhof; 2003). Nevertheless, there is general agreement that the N2 is a marker of general cognitive control. In an ERP study of the Go/Nogo task, Nieuwenhuis, Yeung and Cohen (2004) showed that the usually observed N2 modulation associated with Nogo trials depends on the degree of perceptual overlap (or discriminability) between the Go and Nogo stimuli. More precisely, when Go and Nogo stimuli are easily discriminable, N2 amplitudes for Go and Nogo trials are comparable. Conversely, when the perceptual overlap between both kinds of trials is high, the classic Go/Nogo N2 modulation can be observed, i.e. higher N2 amplitude for the Nogo trials. Nieuwenhuis et al. (2004) explained their findings, regarding Nogo N2 mediation by perceptual overlap, in terms of response conflict. When Go and Nogo stimuli are hard to discriminate (i.e. high perceptual overlap), the Go response is also undeservedly activated when a Nogo trial is presented, which results in a conflict between the Go and the Nogo response, as reflected by an N2 amplification.

Based on the perceptual overlap rationale delineated by Nieuwenhuis et al. (2004), the purpose of the present ERP study is to test the hypothesis that the amount of executive control involved in an RT task with binary choice reactions is determined by the degree of response conflict induced by perceptual overlap between two stimuli. In a choice RT task involving binary choice reactions, the perceptual overlap between the stimuli is arbitrary. And even when two stimuli are subjectively reported to be “easily” discriminable, it remains plausible that response conflict is induced to some extent. Accordingly, the aim of the present study is to demonstrate that in an elementary choice RT task, which does not involve inhibition of prepotent responses and which uses a neutral stimulus-response mapping, the degree of perceptual overlap determines the executive load of the task.

In order to address this research issue, an experiment was designed which evaluates the effects of perceptual overlap on the N2 amplitude of a simple and a choice RT task. Previous research has shown that a choice RT task puts higher demands on executive control than a simple RT task does (Szmalec at al., in press). One possible reason for this is the presence of response conflict in a choice RT task. If such response conflict, which varies with perceptual overlap and is reflected by N2 amplitude, is responsible for the increased executive demands of a choice RT task compared to a simple RT task, the following predictions can be formulated. First, knowing that more executive control is involved in a choice RT task than in a simple RT task, the N2 amplitude is expected to be higher in the choice than in the simple RT task. Second, N2 amplitude is predicted to increase with perceptual overlap in the choice RT task conditions, but not in the simple RT task conditions because the response conflict is assumed not to be present in a simple RT task in which by definition all stimuli lead to the same response.

METHOD

Participants. Thirteen right-handed participants (6 females and 7 males) between the age of 19 and 26 years (mean = 22.50 years) were remunerated for taking part in the study. All participants had normal hearing and they reported being free from neurological or psychiatric problems.

Design and Stimuli. Participants were subjected to a 2 (Task: simple vs. choice RT task) x 3 (Perceptual Overlap: hard vs. intermediate vs. easy discriminability) within-subject design, in a sound-attenuated and electrically shielded room. The stimuli for the choice RT task depended on the degree of perceptual overlap: in the condition with hard discriminability, the first sound was 262 Hz and the second sound 262 Hz + the Just Notable Difference (in Hz), assessed at individual level (see Procedure). In the easy condition, participants performed choice reactions between sounds of 262 and 524 Hz (difference of one octave). In the condition with intermediate discriminability, sounds of 262 and 376 Hz where presented, where the latter is the logarithmic midpoint between 262 and 524 Hz (discriminability is a logarithmic function of the frequency difference). All sounds were 150 msec sinusoidal tones, binaurally presented through a headphone at approximately 60 dB SPL.

***Procedure*.** Prior to the counterbalanced experimental conditions, we determined the Just Notable Difference (JND) at 262 Hz for each participant individually, by using the psychophysical method of constant stimuli (Fechner, 1860). Piloting work suggested that, for the audio parameters and apparatus used in the present study, perfect discriminability for normal hearing and musically untrained subjects could be obtained within a range of 28 Hz from the 262 Hz base sound. Accordingly, stimulus pairs were constructed which consisted of the 262 Hz base sound and a deviant up to 290 Hz (262 + 28) in steps of 2 Hz. This resulted in a set of 14 sound pairs, which were each presented 20 times in a random order. Participants were asked to judge whether they heard a difference between the two sounds in the pair. Then, the JND for this study was determined as the difference in frequency which was recognized in 90% of the trials. A lower percentage would probably produce too low an accuracy and consequently too important a loss of EEG epochs.

After the JND assessment, participants rested for 20 minutes, during which they were prepared for the EEG recording. Then, they went through the six counterbalanced conditions of the experimental design. In each condition, 3 blocks of 120 sounds were presented, which makes a total of 360 sounds per condition. In the choice RT task, participants were instructed to make a left-right response on a response box, as a function of the frequency of the sound. The high tone was mapped to the right key of the response box, the low tone to the left key. For the simple RT task, which requires a simple reaction independent of the frequency of the sounds, 180 trials where responded to with the right hand, the other half with the left hand. In order to prevent that in the simple RT task, participants would respond based on anticipation, rather than responding to the stimulus, we used pseudo-random inter-stimulus intervals (ISIs) of 900 and 1500 msec, with the constraint that no more than three consecutive intervals were of equal duration. Also the randomness of the identity of the sounds was restricted so that no more than three consecutive sounds were of equal frequency. Between each condition, participants rested for five minutes and halfway the experiment, they had a 15 minutes break with the opportunity to drink water. The entire procedure lasted approximately three hours.

EEG recordings. EEG was continuously recorded (bandpass 0.8 – 30 Hz; sample rate = 250 Hz) with tin electrodes at 13 scalp locations (Fz, Cz, Pz, F8, F7, F4, F3, C4, C3, P4, P3, Fp1 and Fp2) of the 10-20 International System, referenced to the nose and with the forehead serving as ground. In order to detect records contaminated with eye movements and blinks, vertical EOG was monitored above the right eye, horizontal EOG at the outer canthus of the right eye. All impedances were below 5 kΩ. All recordings were performed with InstEP hard- and software (Ottawa, Ontario, Canada).

EEG analysis. Trials with a reaction time of less than 100 msec in the simple RT task conditions and less than 150 msec in the choice RT task conditions were regarded as anticipations and hence excluded from further analyses. Similarly, choice RT task trials on which participants made an incorrect choice reaction were discarded. EEG and EOG were filtered with a 1-20 Hz bandpass filter. The EEG and EOG were divided into epochs of 1000 msec time locked to the onset of each stimulus including a 200 msec pre-stimulus baseline. Epochs with amplitude values exceeding ± 75 μV relative to the baseline at any electrode were also discarded. The remaining epochs were averaged per condition.

A dominant frontal topography was obtained for the N2 component. The amplitude and latency of the component were assessed in a 200-400 msec range, by a computer-assisted peak-picking routine. The amplitude of the peaks was scored for each participant by determining the maximum amplitude in the corresponding time-window, and the latency was scored at the maximum amplitude. Both computer-assisted peak-picking and visual inspection failed to recognize an N2 component in the simple RT task conditions.

Statistical analysis. The data from one male subject were discarded from the statistical analyses because in the EEG analysis, 82% of his trails were rejected due to excessive eye-movements. For the other 12 participants, an average of 24% of the trials was rejected due to eye-movements. Behavioral data, N2 latency and N2 amplitude were analyzed by means of repeated measures analyses of variance with the factors Task (simple vs. choice RT task) and Perceptual Overlap (hard vs. intermediate vs. easy discriminability).

RESULTS

JND Estimation. With respect to the JND estimation at 262 Hz, all participants reached perfect discriminability within the 28 Hz range. The mean difference at which 90% of the trials was judged different was 16.83 Hz (SD = 5.42).

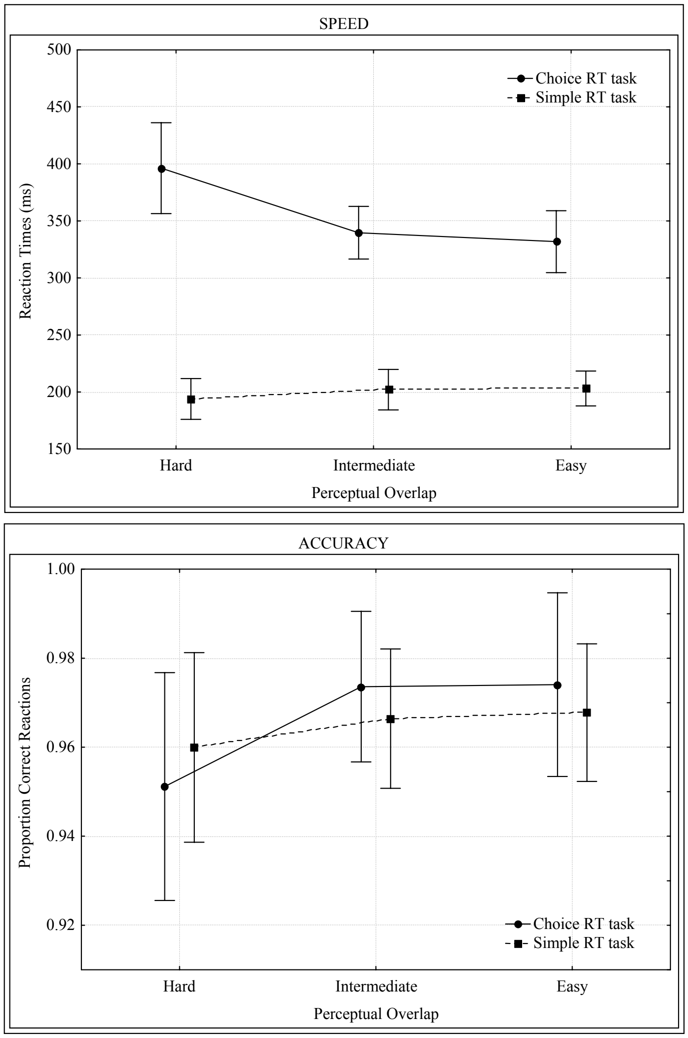

Figure 1. Mean speed (upper panel) and accuracy (lower panel) data for the simple and the choice RT tasks at the different levels of Perceptual Overlap. Vertical bars denote .95 confidence intervals.

Behavioral Results. Mean speed and accuracy data, as a function of the factors Task and Perceptual Overlap, are represented in Figure 1. The main effects of Task and Perceptual Overlap on the reaction times were significant, $F(1, 11) = 166.02$, $p < .001$ and $F(2, 22) = 7.83$, $p < .01$, respectively, as was the interaction, $F(2, 22) = 15.28$, $p < .001$. Planned comparisons revealed that for the choice RT task conditions, reaction times in the condition with hard discriminability were slower than in the condition with intermediate discriminability, $F(1, 11) = 11.17$, $p < .01$, while reaction times in the conditions with intermediate and easy discriminability were performed equally fast, $F < 1$. Perceptual Overlap had no significant effect on the speed of the simple reactions, $F(2, 22) = 1.84$, $p > .10$. A similar pattern of results was observed for the accuracy data.

Electrophysiological Results. The mean amplitude and latency of the N2 as a function of Perceptual Overlap in the choice RT task conditions are presented in Table 1. The stimulus locked ERPs at the frontal scalp site, as a function of Task and Perceptual Overlap, are displayed in Figure 2.

N2 Latency. As described in the EEG analysis section, an N2 peak did not occur in the simple RT task conditions. In the choice RT task conditions, N2 latency was comparable for all three levels of Perceptual Overlap, $F < 1$.

N2 Amplitude. N2 amplitude differed as a function of Perceptual Overlap, $F(2, 22) = 5.38$, $p < .05$. Further planned comparisons revealed that the difference in N2 amplitude between the choice RT task conditions with hard and intermediate discriminability was significant, $F(1, 11) = 8.55$, $p < .01$, while the difference between the intermediate and easy condition was not significant, $F < 1$. The difference in N2 amplitude between the choice RT task conditions with hard and easy discriminability was significant, $F(1, 11) = 5.53$, $p < .05$.

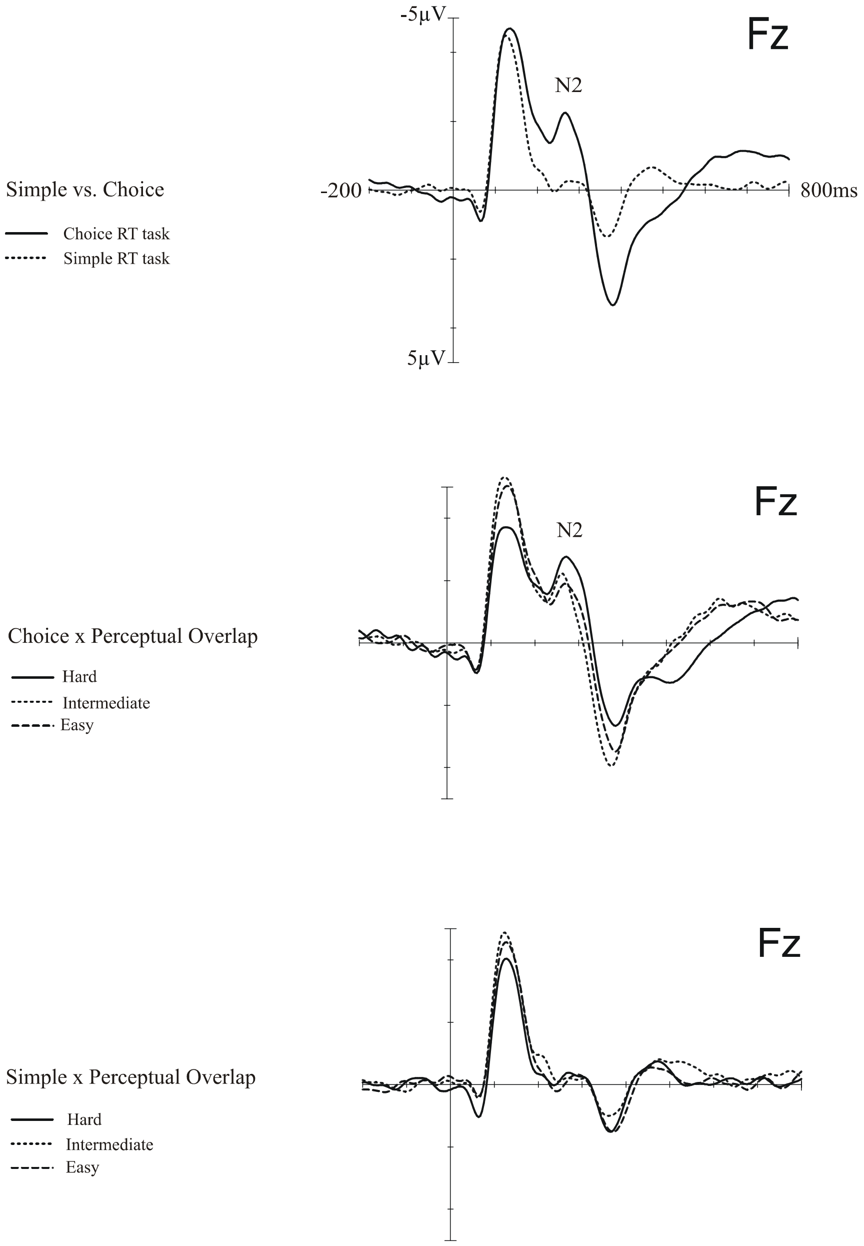

Figure 2: Stimulus-locked ERPs at Fz

	Perceptual Overlap (Discriminability)		
	Hard	Intermediate	Easy
Latency (msec)	262 (39)	262 (37)	257 (32)
Amplitude (μV)	-3.40 (2.21)	-2.59 (2.13)	-2.64 (2.42)

Table 1. Mean N2 latency and amplitude as a function of Perceptual Overlap in the choice RT task conditions. Standard deviations in parentheses.

DISCUSSION

Based on earlier findings which support the position that cognitive control (as reflected by the N2 component of the ERP) involved in a Go/Nogo task is mediated by a response conflict as induced by the perceptual overlap between the Nogo and the Go stimuli, it was hypothesized that the cognitive control exerted in a basic speeded choice RT task (no prepotent responses, neutral stimulus-response mapping) also depends on the degree of perceptual overlap between the stimuli. Accordingly, an experiment was designed in which the N2 amplitude was evaluated while participants performed a single and a choice RT task under three different levels of perceptual overlap (or discriminability).

The behavioral results showed that a binary choice reaction was significantly slower and less accurate when the stimuli were hard to discriminate compared to when they were moderately or easily discriminable. The speed and accuracy of simple reactions were unaffected by the perceptual overlap between the stimuli. With respect to the electrophysiological results, we observed a pattern of N2 modulation in the choice RT task that ran parallel to the behavioral data. More precisely, the N2 amplitude in the condition with high perceptual overlap was significantly higher than in the conditions with intermediate and little perceptual overlap. Based on the assumption that the N2 is a marker of general cognitive processes, the present ERP study supports earlier evidence for executive involvement in a binary choice RT task. But most importantly, on account of the perceptual overlap/response conflict rationale put forward by Nieuwenhuis et al. (2004), we conclude that the extent to which control is involved in a choice RT task depends on the degree of response conflict resulting from the level of perceptual overlap between the stimuli.

A first point that deserves some attention is the finding that no N2 could be detected in the simple RT task conditions. On the one hand, this finding is not surprising given the observed average simple reaction times of approximately 200 msec and given that the N2 is known to occur around 200-400 msec after stimulus onset (Bruin, Wijers, & van Staveren, 2001). But also in theoretical terms, it can be argued that an ERP component indicating response conflict or inhibition is not likely to be found in simple reactions, where all stimuli lead to the same response. On the other hand, some studies have reported an N2 component in a simple RT task. Falkenstein, Hohnsbein and Hoormann (1993), for example, observed an N2 around 230 msec in a simple RT task in which participants reacted in 250 msec on average. The different findings might be due to methodological differences between Falkenstein et al.'s study and the present one. Participants in the Falkenstein et al. study were required to make simple reactions on letters, presented either visually or auditory within blocks, which means that a continuous within-block modality switch was required. Based on the evidence for N2 amplification during task switching in general (Swainson, Cunnington, Jackson, Rorden, Peters, Morris et al., 2003) it cannot be excluded that the dimensional switch in the Falkenstein et al. study might have produced the observed N2. In any case, the absence of an N2 in the present simple RT task conditions is an important finding. As far as the N2 is concerned, it means that cognitive control is not measurably involved in a simple RT task and that any information processing involving a choice reaction requires cognitive control (Carbonnell et al., 2004).

Next, a theoretical account of executive involvement in a choice RT task will be formulated, on the basis of both the present and earlier findings. As described in the introduction, there exists EMG and behavioral evidence for the involvement of general cognitive control mechanisms in a choice RT task. In addition to this, a number of studies observed EMG and ERP indicators of response inhibition in the same task, which makes response inhibition a source or maybe the source of executive involvement in the choice RT task. The present experiment provided ERP evidence in support of the position that the extent of executive control exerted in a choice RT task, depends on the degree of perceptual overlap between the stimuli. In our view, these findings can be integrated as follows. In a choice RT task, a response must be selected as a function of the identity of a stimulus. When a target stimulus is presented, the response alternatives are activated (Carbonnell et al., 2004) and a state of response conflict is induced. This conflict situation is detected, presumably at the level of the ACC, and top-down control is engaged to resolve this conflict (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Carbonnell et al.'s (2004) findings suggest that response inhibition is presumably the cognitive control mechanism which suppresses the activation of the erroneous response alternatives (see also Burle et al., in press). Presumably, the amount of inhibition or cognitive control that must be exerted is not a constant but it depends on the degree of activation of the incorrect response alternatives or in other words, on the degree of response conflict. Now, Nieuwenhuis et al. (2004) and the present findings suggest that response conflict or the difference in activation between the correct and incorrect response is a function of the degree of perceptual overlap between the stimuli. Hence, the conclusion that the amount of executive control (or response inhibition according to Carbonnell et al., 2004; Burle et al., in press) exerted in a choice RT task is related to the level of perceptual overlap, is straightforward. Thus, when a person for example performs a choice reaction between two hardly discriminable stimuli, both response alternatives are highly activated and a severe response conflict is induced. Hence, top-down control imposes high demands on response inhibition in order to suppress the activation of the erroneous alternative, so that the correct response can be executed. In such a centrally demanding situation, a higher N2 is expected, irrespective of whether it specifically reflects the response conflict or the response inhibition.

It should finally be noted that in the present study, we used the N2 as a marker of cognitive control because, like earlier studies (e.g. Nieuwenhuis et al., 2004), also the present experiment does not allow to dissociate the response inhibition and response conflict accounts of the N2. But that does not undermine the main claim of this study, which states that the amount of executive control required to perform a choice reaction is related to the degree of response conflict induced by the perceptual overlap between the task stimuli. This conclusion implies that the physical resemblance between stimuli can have important cognitive implications and that researchers should be aware of these implications when determining stimulus parameters. At the same time, the present finding corroborates the view that any task requiring choice reaction also involves some degree of cognitive control to handle the response conflict.

REFERENCES

Allain, S., Carbonnell, L., Burle, B., Hasbroucq, T., & Vidal, F. (2004). On-line executive control: An electromyographic study. *Psychophysiology, 41*, 113-116.

Botvinick, M., Braver, T., Barch, D. Carter, C. & Cohen, J. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*, 625-652.

Botvinick, M.M., Cohen, J.D., & Carter, C.S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences*, *8*, 639-646.

Bruin, K.J., Wijers, A.A., & Van Staveren, A.S.J. (2001). Response priming in a Go/Nogo task: Do we have to explain the Go/Nogo N2 effect in terms of response activation instead of inhibition? *Clinical Neurophysiology, 112*, 1660-1671.

Burle, B., Vidal, F., Tandonnet, C., & Hasbroucq, T. (in press). Physiological evidence for response inhibition in choice reaction time tasks. *Brain & Cognition.*

Carbonnell, L., Hasbroucq, T., Grapperon, J., & Vidal, F. (2004). Response selection and motor areas: A behavioural and electrophysiological study. *Clinical Neurophysiology, 115*, 2164-2174.

Falkenstein, M., Hohnsbein, J., & Hoormann, J. (1993). Late visual and auditory Erp components and choice-reaction time. *Biological Psychology, 35*, 201-224.

Falkenstein, M., Hoormann, J., & Hohnsbein, J. (1999). Erp components in Go/Nogo tasks and their relation to inhibition. *Acta Psychologica, 101*, 267-291.

Fechner, G.T. (1860). *Elemente der Psychophysik*. Leipzig: Breitkopf und Härtel, 2, p. 559.

Klauer, K.C., & Stegmaier, R. (1997). Interference in immediate spatial memory: Shifts of spatial attention or central-executive involvement? *Quarterly Journal of Experimental Psychology, 50A*, 79-99.

Kok, A. (1986). Effects of degradation of visual stimulation on components of the event-related potential (ERP) in GO/No-Go reaction tasks. *Biological Psychology, 23*, 21-38.

Nieuwenhuis, S., Yeung, N., & Cohen, J.D. (2004). Stimulus modality, perceptual overlap, and the Go/No-Go N2. *Psychophysiology, 41*, 157-160.

Nieuwenhuis, S., Yeung, N., van den Wildenberg, W.P.M., & Ridderinkhof, K.R. (2003). Electrophysiological correlates of anterior cingulate function in a go/nogo task: Effects of response conflict and trial-type frequency. *Cognitive, Affective, and Behavioral Neuroscience, 3*, 17-26.

Swainson, R., Cunnington, R., Jackson, G.M., Rorden, C., Peters, A.M., Morris, P.G., & Jackson, S.R. (2003). Cognitive control mechanisms revealed by Erp and Fmri: Evidence from repeated task-switching. *Journal of Cognitive Neuroscience, 15*, 785-799.

Szmalec, A., Vandierendonck, A., & Kemps, E. (in press). Response selection involves executive control: Evidence from the selective interference paradigm. *Memory & Cognition*.

CHAPTER 5

EXPLORING THE SOURCES OF EXECUTIVE INVOLVEMENT IN A ONE-BACK CHOICE RT TASK

***Work in progress*[1][2]**

INTRODUCTION

In Chapter 3 of this dissertation, we introduced the one-back choice RT task with auditory stimuli and estimated the executive demands of this task by means of the selective interference paradigm, within Baddeley's (1986) Working Memory framework. It was concluded that the one-back choice RT task demands more executive control than a standard choice RT task and that the effects of the one-back task do not seem to be contaminated by the slave systems. In this chapter, we attempt to further clarify the finding that the requirement to delay a choice reaction until the onset of the next stimulus (one-back) is an operation that involves executive control. It is at this point unclear what the source of this executive involvement is.

One of the hypotheses we have put forward in Chapter 3 is that the additional executive demands of the one-back choice RT task – compared to the standard choice RT task – originate from a temporal overlap between the processing of two consecutive one-back choice reactions. As can be seen in Figure 1, this temporal overlap lays in the fact that stimulus X is already presented before the response to stimulus X-1 is terminated. The question the present study addresses is whether this temporal overlap produces a

---

[1] In collaboration with Ans Vercammen, Frederick Verbruggen and André Vandierendonck.

[2] One important future direction of the research project outlined in this dissertation is aimed to gain an insight into the cognitive processes involved in a one-back choice RT task. Chapter 5 presents early results from recent empirical work that is a first step in addressing this issue.

competition between the cognitive processing associated with the choice reactions to stimulus X-1 and stimulus X.

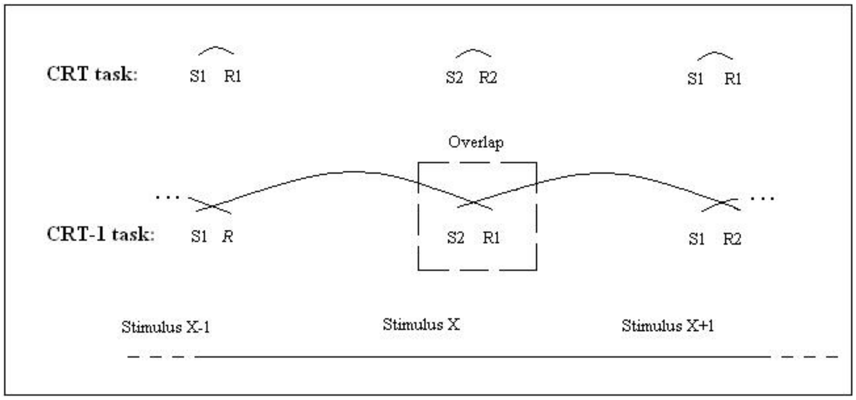

Figure 1. Schematic representation of the standard choice RT task (CRT) and the one-back choice RT task (CRT-1), in which three successive trials are presented (stimuli X-1, X and X-1). In this example, the three subsequent stimuli are a low pitch tone (S1), a high pitch tone (S2) and again a low pitch tone. R1 and R2 represent a reaction to an S1 stimulus and to an S2 stimulus, respectively.

In essence, stimulus X in a one-back choice RT task functions as a trigger for the response to stimulus X-1. But at the same time, the identity of stimulus X is relevant since participants know that a response on stimulus X is required on presentation of stimulus X+1. This implies that at a certain moment in time, also the cognitive processing of (trigger) stimulus X must begin and the key question is whether this occurs before or after the reaction on stimulus X-1 is terminated? Or to put it differently: is stimulus X instantly processed or is its processing delayed until the reaction to stimulus X-1 has been given? On the one hand, participants might process (trigger) stimulus X after the previous choice reaction (i.e. on stimulus X-1) has been completed. The observation that a one-back choice reaction lasts approximately 450 msec (Chapter 3) would in the latter case imply that the cognitive processing of stimulus X is initiated only 450 msec after its onset and that participants have to rely on perceptual (echoic) memory in order to bridge this period. On the other hand, participants might not be able to efficiently bridge the 450 msec delay period relying on echoic memory and they might thus process stimulus X immediately after its presentation, i.e. prior to the response execution associated with stimulus X-1. The immediate processing of stimulus X would then offer the possibility to construct a more decay-resistant representation of task-relevant information (e.g. a memory representation rather than a sensory representation of the stimulus) in order to bridge the 450 msec period prior to the X-1 response. It should be noted that the latter account has important implications for the executive demands of the task. If the processing of stimulus X is engaged while the processing of stimulus X-1 is not yet finished (at least the response has not been executed), a cognitive conflict situation is likely to occur. The reason is that the processing of stimulus X might produce irrelevant S-R information that can conflict with the processing of stimulus X-1, analogous to effects of irrelevant stimuli or irrelevant stimulus dimensions observed in conflict tasks such as the Eriksen flanker task (Eriksen & Eriksen, 1974) or the Stroop task (Stroop, 1935; MacLead, 1991), respectively.

Accordingly, the present experiment was designed to investigate whether participants in a one-back choice RT task start the cognitive processing of stimulus X before the reaction to stimulus X-1 is terminated. It is supposed that the additional executive demands of a one-back choice RT task, compared to a standard choice RT task, are due to a cognitive conflict that arises from this overlap between the processing of subsequent stimuli. To this end, behavioral measures were complemented with three electrophysiological measures (the N2, the P3 and also the LRP). They are discussed in more detail below.

The N2 is a negative deflection of the Event Related brain Potential (ERP) with a frontocentral topography, which peaks around 200-400 msec after the onset of the stimulus. It is believed to reflect activation of the Anterior Cingulate Cortex (ACC; Liotti, Woldorff, Perez, & Mayberg, 2000). The N2 component is a widely used measure of executive control (Nieuwenhuis, Yeung, & Cohen, 2004). In the task switching paradigm for example, it has been demonstrated that N2 amplitude is larger for task alternation trials compared to task repetition trials (Swainson, Cunnington, Jackson, Rorden, Peters, Morris, et al., 2003). In the inhibition literature, it is a well replicated finding that suppression of prepotent responses, such as in a Go/Nogo task, is reflected by N2 amplification (Falkenstein, Hoormann, & Hohnsbein, 1999). The most acknowledged theoretical account of the N2 is that it is an ERP correlate of response conflict (Yeung, Botvinick, & Cohen, 2004). This is evidenced by broad empirical support for the position that N2 amplitude increases as a function of the amount of response conflict in several cognitive tasks (e.g. Eriksen flanker task, Go/Nogo task, Stroop task).

The second electrophysiological measure that was investigated in relation to the one-back choice RT task is the classical P3 (or P3b). The P3 component is a positive deflection with a parietal distribution. There is general agreement that P3 does not reflect activity of one particular brain structure but rather the activity of various distributed brain areas (Kok, 2001). Most researchers agree that the P3 is associated with stimulus-related, rather than response-related processing and in this regard, the component is assumed to be evoked when the evaluation of a stimulus is terminated (Doucet & Stelmack, 1999). In most ERP studies, the P3 is used as a general marker of cognitive processing whose amplitude reflects the mental activity that is invested in a task. Particularly relevant for the present study is the fact that P3 amplitude is known to decrease when the attentional load of a task increases (Joppich, Dauper, Dengler, Johannes, Rodriguez-Fornelis, & Munte, 2004; Kok, 2001). In this context, reduced P3 amplitude is assumed to indicate a greater consumption of attentional resources (Joppich et al., 2004).

A third ERP measure that was used in this study is the Lateralized Readiness Potential (LRP). The LRP is a negative shift in the EEG of the motor cortex that precedes motor activity. It has been considered a sensitive measure of motor activation or preparation (Coles, 1989; Miller & Hackley, 1992). In the present study, the LRP was used in order to trace the time course of motor activation in the one-back choice RT task. As will be described in what follows, according to the movement preparation literature, the requirement to delay a response until the onset of the following stimulus might have implications at the level of the LRP. An important line of research in the movement preparation literature is the precuing technique initially put forward by Rosenbaum (1980, 1983). In Rosenbaum's precuing paradigm, a cue that is presented prior to the onset of a target stimulus, may provide the (or part of the) defining parameters of the required response, allowing (partial) movement preparation. It has been demonstrated that also precues elicit an LRP, which is called the *foreperiod* LRP (e.g., Wild-Wall, Sangals, Sommer, & Leuthold, 2003), referring to the fact that it occurs in the period between the precue and the target stimulus. In addition, a number of studies showed that the amplitude of the foreperiod LRP is a function of the degree of stimulus information that is contained in the precue (Leuthold, Sommer, & Ulrich, 1996; Ulrich, Leuthold, & Sommer, 1998). More precisely, when the precue is fully informative about the forthcoming target stimulus, foreperiod LRP amplitude is larger compared to when the precue only provides a restricted number of parameters of the target stimulus. Another important finding in movement preparation research is that the presence of precue information shortens the motor part of the reaction time on the target stimulus (e.g. Müller-Gethmann, Rinkenauer, Stahl, & Ulrich, 2000). This is evidenced by the observation that in the response-locked lateralized motor potentials, the onset of the *late* LRP is delayed when stimulus-information is precued (i.e. when a foreperiod LRP is elicited) compared to when no precues are available. The reason why these LRP findings associated with movement preparation are summarized here, is because the one-back choice RT task in principle permits motor preparation. If we regard stimulus X-1 in the one-back choice RT task as a (fully informative) precue for the response that is required after presentation of stimulus X, motor preparation should be possible.

For the current research goals, an experiment was designed in which the ERP correlates mentioned before were measured during a standard choice

RT task and a one-back choice RT task with auditory stimuli. In addition, the perceptual overlap of the stimuli was manipulated in two levels: easy and hard discriminability. A few studies (Nieuwenhuis et al., 2004; Chapter 4) have demonstrated that increasing the perceptual overlap of stimuli in a choice RT task (i.e. decreasing the perceptual discriminability) increases the amplitude of the N2 component. This finding was explained in terms of response conflict theory which supposes that under conditions of high perceptual overlap, the incorrect response is more activated than under conditions of low perceptual overlap. Accordingly, a stronger response conflict (between the correct and incorrect responses) is induced under conditions of high perceptual overlap, as evidenced by N2 amplification. The perceptual overlap manipulation was implemented in the present experimental design in order to investigate whether N2 amplitude varies with stimulus discriminability, not only in the standard choice RT task but also in the one-back choice RT task. The occurrence of a response conflict in the interval between the presentation of stimulus X and the response to stimulus X-1 would be supportive of the assumption that (trigger) stimulus X is instantly processed to the level of response activation, concurrently with the final processing of the previous stimulus X-1.

In view of the research issue that is addressed in the present study, we hypothesize that participants in a one-back choice RT task engage cognitive processing of stimulus X before the response to stimulus X-1 has been terminated, so that a cognitive conflict is anticipated to occur. If this assumption is correct, the following predictions regarding the electrophysiological correlates of the one-back task should be confirmed.

First, if (trigger) stimulus X in the one-back choice RT task is instantly processed (i.e. the cognitive processing of stimulus X is not delayed until the response on X-1 is made), and this early processing proceeds until the stage of response activation, we predict that response conflict will be detectable in the one-back task by means of an effect of perceptual overlap on N2 amplitude, similarly to what has been found in a standard choice RT task

(Nieuwenhuis et al., 2004; Chapter 4). At the same time, we anticipate that by analogy with motor preparation findings, the final motor activation for response X (which is then after presentation of stimulus X+1) will benefit from the early processing of stimulus X that has occurred prior to the response to stimulus X-1. This should be reflected in a delayed response locked late LRP onset for the one-back choice RT task (Müller-Gethmann et al., 2003; Wild-Wall et al., 2003). Second, if cognitive processing of stimulus X begins prior to response X-1 (see previous prediction), we anticipate a conflict to occur between the information processing of stimulus X and stimulus X-1. In that case, larger N2 amplitude is expected in the one-back choice RT task than in the standard choice RT task. The third prediction concerns the amplitude of the P3 component. It has been demonstrated that P3 amplitude is smaller in those tasks that consume more executive resources (Joppich et al., 2004; Kok, 2001). In this view and based on earlier evidence for higher executive demands in a one-back than in a standard choice RT task, we expect P3 amplitude to be smallest in the one-back task. It should finally be noted that no straightforward prediction is made regarding a potential foreperiod LRP in the one-back task, although this EEG measure is known to be involved in motor preparation. The reason is that in the one-back task, foreperiod LRP (provided that it does occur) as well as late LRP are presumed to be elicited at about the same time: the foreperiod LRP associated with stimulus X should logically coincide with the response activation related to stimulus X-1. By consequence, the examination of foreperiod LRP will be on an exploratory basis.

METHOD

Participants. Fourteen right-handed participants (7 females and 7 males) were remunerated for taking part in the study. All participants reported being free from neurological or psychiatric problems, had normal hearing and normal or corrected-to-normal vision. One male subject was discarded from the sample because more than 80% of his data were rejected for excessive artifacts. The mean age of the remaining thirteen participants was 25.38 years, ranging from 21 to 31 years.

Design and Stimuli. Participants were subjected to a 2 (Task: standard vs. one-back choice RT task) x 2 (Perceptual Overlap: hard vs. easy discriminability) within-subject design. The four conditions were manipulated between blocks and the order of the blocks was counterbalanced across subjects. The Perceptual Overlap manipulation was obtained as follows: in the (standard choice RT task and one-back choice RT task) conditions with hard discriminability, the first sound was 262 Hz and the second sound 262 Hz + the Just Notable Difference (in Hz), assessed at individual level (see *Procedure*). In the conditions with easy discriminability, participants performed standard and one-back choice reactions between sounds of 262 and 524 Hz (difference of one octave). All sounds were 150 msec sinusoidal tones, binaurally presented through a headphone at approximately 60 dB SPL.

Procedure. Prior to the counterbalanced experimental conditions, the Just Notable Difference (JND) at 262 Hz was measured for each participant individually by using the psychophysical method of constant stimuli (Fechner, 1860). To this end, stimulus pairs were constructed which consisted of a 262 Hz base sound and a variable deviant sound. This deviant sound measured between 0 and 28 Hz (in steps of 2 Hz) more than the 262 Hz base sound. This resulted in a set of 14 sound pairs, which were each presented 20 times in a random order. Participants were required to judge whether they heard a difference between the two sounds in the pair. For this study, we assigned the participants' difference threshold at the level of discriminability that was reported to be different in 90% of the trials. It was decided not to use a lower percentage in order to avoid too low an accuracy and consequently too important a loss of EEG epochs in the actual experiment.

After the JND assessment, participants practiced both RT tasks until they met a criterion of consecutively 20 correct (standard and one-back) choice reactions. Then, they rested for 20 minutes, during which they were prepared for the EEG recording. Next, the participants went through the four counterbalanced conditions of the experimental design. In each condition, 3 blocks of 120 sounds were presented, which makes a total of 360 sounds per condition and thus a total of 1440 experimental trials. In the standard choice RT task, a left-right response on a response box was required, based on the pitch of the sound. The high tone was mapped to the right key of the response box, the low tone to the left key. In the one-back choice RT task, participants were demanded to delay the choice reaction until the occurrence of the next stimulus or in other words to respond to the pitch of the previous sound (one-back). In order to avoid anticipations, especially in the one-back choice RT task, pseudo-random inter-stimulus intervals (ISIs) of 1500 and 2500 msec were used. Between each condition, participants rested for five minutes and halfway the experimental blocks, they were offered a 15 minutes break with the opportunity to drink water. The entire experimental procedure lasted approximately three hours.

EEG recordings. The electroencephalogram was continuously recorded (bandpass 0.8 – 30 Hz; sample rate = 512 Hz with Ag/AgCl electrodes at 19 scalp locations (Fp1, Fp2, AFz, F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4 and Oz) of the 10-20 International System. Horizontal EOG was recorded at the outer canthi and vertical EOG above and below the left eye. The ground electrode was placed on the forehead. All impedances were kept below 5 kΩ.

EEG analysis. Trials with a reaction time of less than 150 msec in the standard choice RT task conditions and less than 100 msec in the one-back choice RT task conditions were regarded as anticipations and excluded from further analyses. Similarly, trials on which participants made an incorrect choice reaction were discarded (cfr. Behavioral results). EEG and EOG were filtered with a 1-20 Hz bandpass filter. For the stimulus-locked analyses, the

EEG and EOG were divided into epochs of 1200 msec time locked to the onset of each stimulus and referred to a 200 msec pre-stimulus baseline. For the response-locked analyses, the epochs started 800 msec before until 200 msec after the response was given. The 200 msec response-locked baseline ran from 1000 msec until 800 msec prior to the response. Epochs with amplitude values exceeding ± 75 µV relative to the baseline at any electrode were discarded. The remaining epochs were averaged per condition.

The N2 and P3 components of the ERP were examined on the frontal (Fz) and parietal (Pz) scalp sites, respectively. The amplitude and latency of the components were assessed by a computer-assisted peak-picking routine in the 200-400 msec range for the N2 and in the 200-500 msec range for the P3. The amplitude of the peaks was scored for each participant by determining the maximum amplitude in the corresponding time-window, and the latency was scored at the maximum amplitude. The LRP was defined as the difference between the electrodes (C3 and C4) ipsi- and contralateral to the responding hand over the primary motor cortices (i.e. $((C3\text{-}C4)_{\text{right}} + (C4\text{-}C3)_{\text{left}})/2$), calculated per participant, per condition at the average C3 and C4 waveforms. The amplitude of the LRP was assessed by a computer-assisted peak-picking routine and the LRP onset was defined at 50% of the maximum value of the LRP observed in the condition (Mordkoff & Gianaros, 2000).

Statistical analysis. Behavioral data, N2 and P3 amplitudes and latencies as well as LRP amplitudes and onsets were analyzed by means of repeated measures analyses of variance with the factors Task (standard vs. one-back choice RT task) and Perceptual Overlap (hard vs. easy discriminability).

RESULTS

JND estimation. All participants reached the point of 100% reported discriminability within the 28 Hz range above 262Hz. The mean 90% difference threshold at 262Hz was 14.42 Hz (*SD = 4.07*).

Behavioral results. Mean speed and accuracy data, as a function of the factors Task and Perceptual Overlap, are represented in Figure 2. With respect to the latencies, we observed significant main effects of Task and Perceptual Overlap and a significant interaction of both factors, $F(1, 12) = 7.25$, $p < .05$, $F(1, 12) = 22.81$, $p < .001$, and $F(1, 12) = 22.55$, $p < .001$, respectively. Planned comparisons showed that standard choice reactions were performed faster when the sounds were easily discriminable compared to when they were hard to discriminate, $F(1, 12) = 67.89$, $p < .001$. The one-back choice RT task however was performed equally fast under both conditions of discriminability, $F(1, 12) = 1.09$, $p > .30$. Regarding the accuracy data, we observed significant main effects of Task and Perceptual Overlap, $F(1, 12) = 16.66$, $p < .01$ and $F(1, 12) = 11.59$, $p < .01$, respectively. The lack of interaction between both factors points towards a similar decline in accuracy for both RT tasks when the stimuli were hard to discriminate, $F(1, 12) = 2.18$, $p > .10$.

Electrophysiological results. *N2.* The grand average stimulus-locked ERPs at the Fz frontal scalp site, as a function of Task and Perceptual Overlap, are displayed in Figure 3. Neither of the main effects (Task, $F < 1$, Perceptual Overlap, $F(1, 12) = 1.38$, $p > .20$), nor the interaction between both factors, $F < 1$, on N2 *latency* was significant. With respect to the N2 *amplitude* data, we observed a significant main effect of Perceptual Overlap, $F(1, 12) = 15.37$, $p < .01$, while the main effect of Task and the interaction between Task and Perceptual Overlap were not significant (both F's < 1). Planned comparisons revealed that N2 amplitude increased with perceptual overlap in the standard choice RT task, $F(1, 12) = 13.99$, $p < .01$, as well as in the one-back choice RT task, $F(1, 12) = 10.29$, $p < .01$.

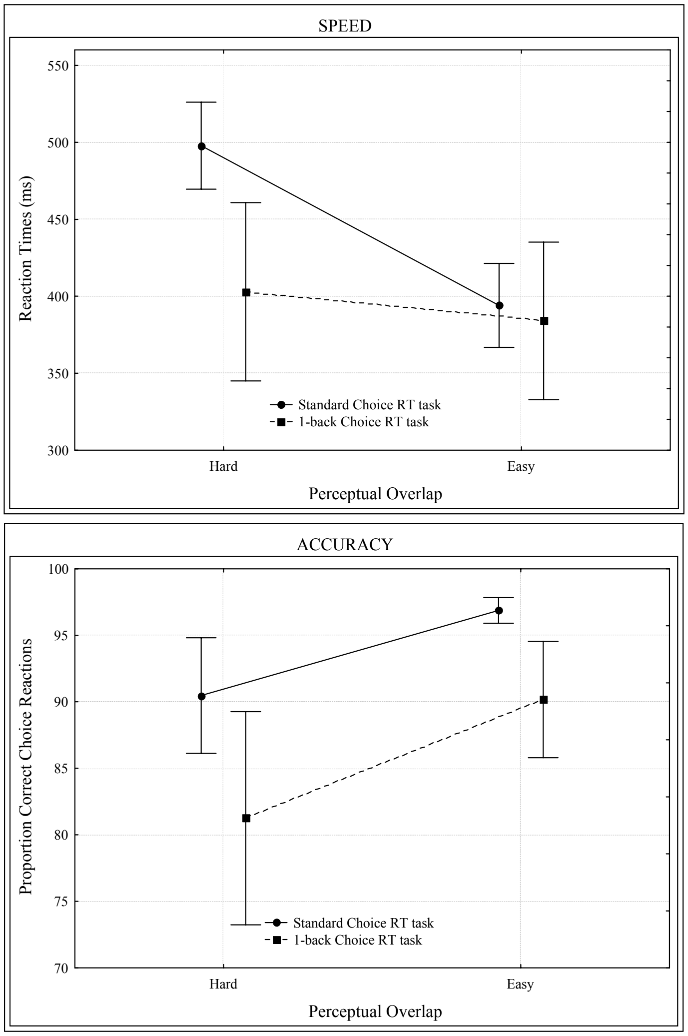

Figure 2: Mean speed (upper panel) and accuracy (lower panel) data for the standard choice RT task and the one-back choice RT task under conditions of hard and easy discriminability. Vertical bars denote .95 confidence intervals.

Stimulus-locked P3. Grand average stimulus-locked ERPs at the Pz scalp site, as a function of Task and Perceptual Overlap, are displayed in Figure 4.

We observed a significant main effect of Task on P3 *latency*, indicating that the P3 component occurred earlier in the one-back choice RT task, $F(1, 12) = 5.95$, $p < .05$. The significant main effect of Perceptual Overlap shows that P3 peaked earlier under conditions of small perceptual overlap, $F(1, 12) = 20.16$, $p < .001$. Also the interaction Task x Perceptual Overlap was statistically reliable, $F(1, 12) = 8.82$, $p < .05$. Planned comparisons revealed that Perceptual Overlap significantly affected P3 latency in the standard choice RT task, $F(1, 12) = 16.97$, $p < .01$, but not in the one-back choice RT task, $F(1, 12) = 1.96$, $p > .10$.

Furthermore, a significant main effect of Task revealed that P3 *amplitude* was significantly smaller in the one-back choice RT task, than in the standard choice RT task, $F(1, 12) = 41.87$, $p < .01$. The main effect of Perceptual Overlap showed that P3 amplitude was smaller when stimuli were here hard to discriminate compared to when they were easily discriminable, $F(1, 12) = 19.18$, $p < .001$. The interaction of Task and Perceptual Overlap was not significant, $F(1, 12) = 1.95$, $p > .10$.

Response-locked P3. The stimulus-locked analyses at Pz indicate that P3 amplitude was smaller for the one-back choice RT task than for the standard choice RT task, and that P3 amplitude decreased with increasing perceptual overlap. In order to rule out the alternative explanation that these reductions in P3 amplitude are an artifact of the higher variability in reaction times (see Figure 2), the Pz waveforms were locked to the onset of the response. The results are illustrated in Figure 5. In the response-locked analyses, we still observed a significantly lower late positivity in the one-back choice RT task than in the standard choice RT task, $F(1, 12) = 16.34$, $p < .01$. The interaction Task x Perceptual Overlap was marginally significant, $F(1, 12) = 3.53$, $p = .08$. Planned comparisons showed that in the standard choice RT task, the Pz waveforms were comparable for both levels of perceptual overlap, $F < 1$. In the one-back choice RT task, the late positivity was smaller when the stimuli were harder to discriminate, $F(1, 12) = 9.05$, $p < .01$.

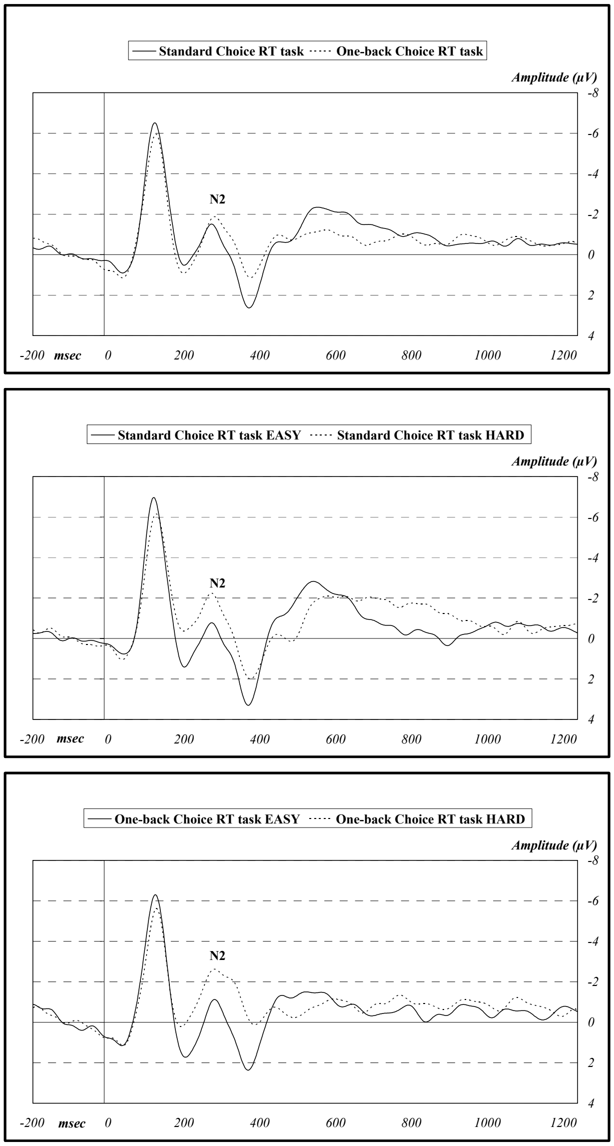

Figure 3: Stimulus-locked ERPs at the Fz electrode, illustrating the main effect of Task (upper panel) and the effect of Perceptual Overlap on the Standard Choice RT task (middle panel) and on the One-back Choice RT task (lower panel).

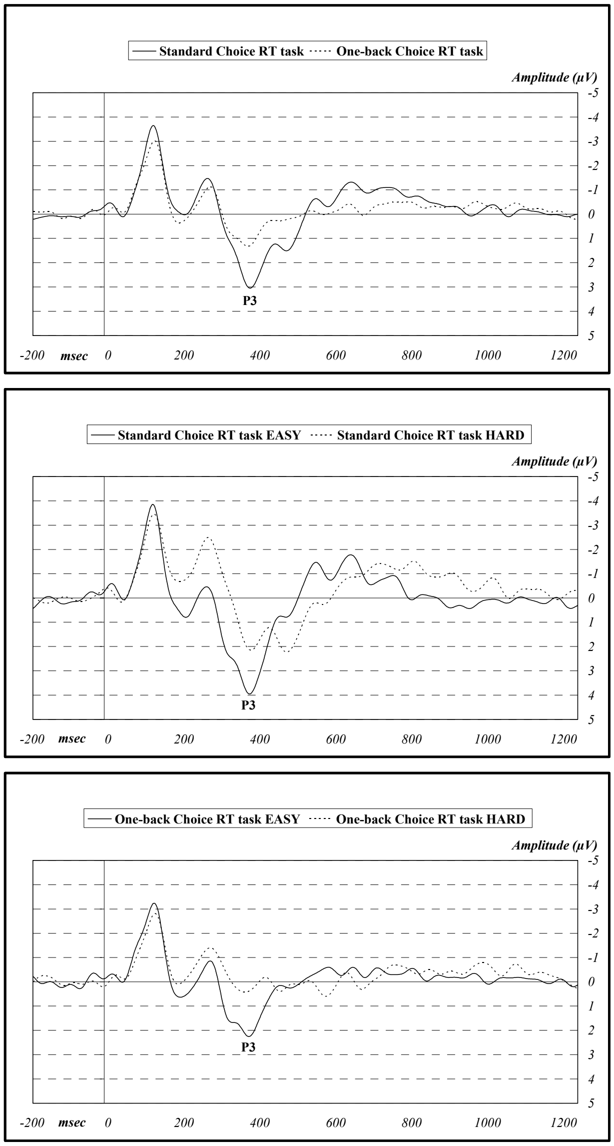

Figure 4: Stimulus-locked ERPs at the Pz electrode, illustrating the main effect of Task (upper panel) and the effect of Perceptual Overlap on the standard Choice RT task (middle panel) and on the One-back Choice RT task (lower panel).

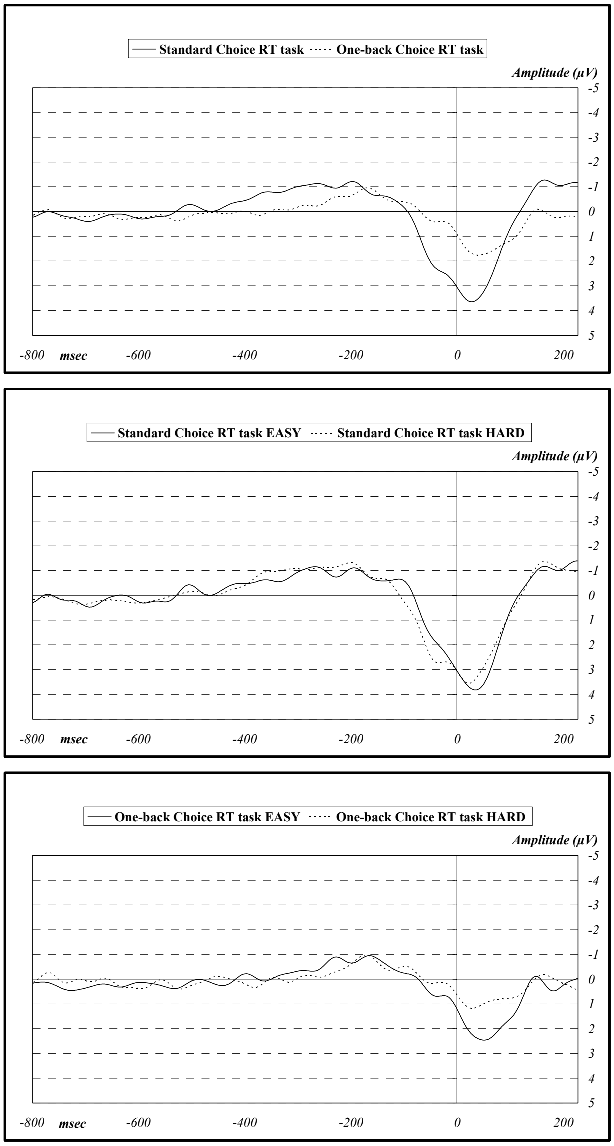

Figure 5. Response-locked ERPs at the Pz electrode, illustrating the main effect of Task (upper panel) and the effect of Perceptual Overlap on the Standard Choice RT task (middle panel) and on the One-back Choice RT task (lower panel).

LRP. We analyzed the LRP waveforms locked to the onset of the response (Figure 6). These analyses revealed a significant main effect of Task on the LRP *onset*, $F(1, 12) = 11.06$, $p < .01$, pointing towards a later onset in the one-back choice RT task. The main effects of Task and the interaction Task x Perceptual Overlap on LRP onset were not significant, $F < 1$, and, $F(1, 12) = 2.67$, $p > .10$, respectively. Similarly, on LRP *amplitude,* we observed a significant main effect of Task, $F(1, 12) = 21.63$, $p < .001$, whereas the main effect of Perceptual Overlap and the interaction between both factors were not significant (both F's < 1). Note that since the analyses revealed no reliable effect of or interactions with the factor Perceptual Overlap, the waveforms shown in Figure 6 are averaged over both levels of discriminability.

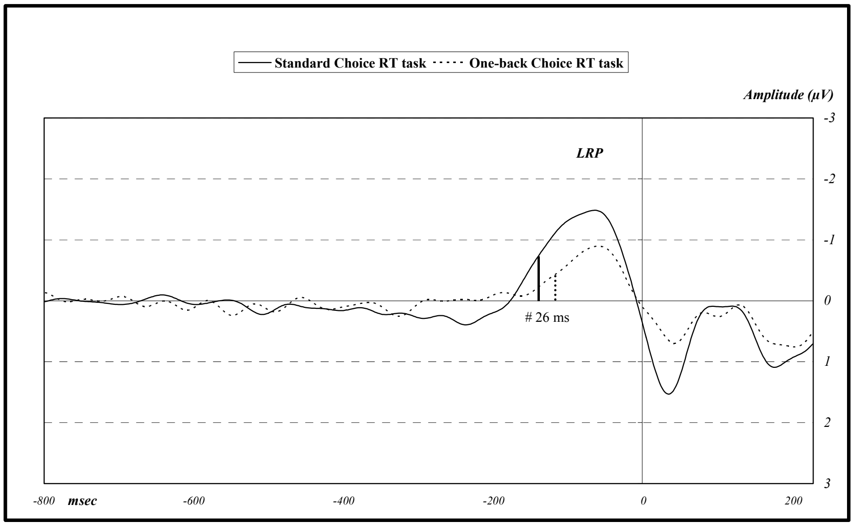

Figure 6. Lateralized Readiness Potentials associated with the standard choice RT task and the one-back choice RT task. The grand average waveforms are locked to the onset of the response.

DISCUSSION

In a one-back choice RT task, the reaction to a target stimulus is delayed until the presentation of the next stimulus (see Figure 1). It has been demonstrated that this one-back delay involves additional executive resources compared to a standard choice RT task, in which participants instantly respond to the target stimulus (Chapter 3). It is at present unclear what causes the additional executive demands of the one-back choice RT task. One potential explanation may be related to the fact that in the one-back choice RT task, the processing of a given stimulus X-1 is still going on at the time the next stimulus X is presented. If participants start the cognitive processing of the new stimulus X before the choice reaction to stimulus X-1 is terminated, a cognitive conflict is assumed to occur. The present experiment was designed to test this assumption.

First, we predicted that in the one-back choice RT task, stimulus X is processed before the choice reaction to stimulus X-1 is terminated. The data show that in the one-back choice RT task, like in the choice RT task, the N2 was amplified with increasing perceptual overlap. According to the perceptual overlap/response conflict theory (Nieuwenhuis et al., 2004), this suggests that (trigger) stimulus X is processed until the stage of response activation, even before the response to X-1 has been executed, through which the first prediction is empirically supported. Second, we predicted that the early cognitive processing of stimulus X (i.e. prior to the reaction to stimulus X-1) is likely to induce a cognitive conflict between the choice reactions to stimuli X and X-1 and therefore we anticipated that N2 amplitude would be larger in the one-back than in the standard choice RT task. This prediction was not supported by the present findings. Later in this discussion, we will come back to this finding. Regarding the third prediction, we observed that P3 amplitude was smaller in the one-back than in the standard choice RT task, which still does point towards a larger consumption of executive resources in the one-back task (Joppich et al., 2004).

The findings further demonstrated that the one-back choice RT task differed from the standard choice RT task both in terms of onset and amplitude of the late lateralized readiness potential. In essence, the one-back task can be regarded as a temporal manipulation of the standard choice RT task in the sense that the choice reaction must be delayed, but the processing stages as such are basically the same. Nevertheless, the onset of the (response-locked) motor potential occurred later (26 msec on average) in the one-back task than in the standard choice RT task or in other words, the motor portion of the reaction time was (26 msec) shorter in the one-back task. As we described in the introduction, such an RT shortening is typically observed when advance information, such as a precue, is available and the motor response can by consequence be prepared (Müller-Gethman et al., 2000). In this view, the onset differences on the *late* LRP observed in the current study suggest that motor preparation was possible in the one-back choice RT task. Moreover, according to the same motor preparation literature, if motor preparation is involved in the one-back choice RT task, a *foreperiod* LRP is expected prior to the late LRP, as an index of early motor activation. More precisely, foreperiod LRP is assumed to follow on the presentation of (trigger) stimulus X, presumably shortly before the late LRP, the latter reflecting motor activation for the response to stimulus X-1. In the present data, only a late LRP component was visible. Identification of a foreperiod LRP seems problematic in the one-back choice RT task, probably because foreperiod LRP for a given stimulus X coincides with the late LRP for the response to X-1 so that both motor potentials are elicited in the same S-R interval and they might by consequence not be distinguishable. In addition, when stimulus X-1 and stimulus X are different (i.e. high tone vs. low tone), foreperiod LRP and late LRP will be elicited in the opposite motor cortices and this might, as will be described in what follows, have implications for the resulting LRP amplitude.

This brings us to the difference in LRP amplitude between both RT tasks. Based on the relevant literature, two main explanations for this finding can be formulated. First, a number of studies have shown that the magnitude of a late LRP decreases as a function of the degree of motor preparation (i.e. the extent to which the foreperiod LRP has already activated the response; Willemssen, Hoormann, Hohnsbein, & Falkenstein, 2004). Second, it has been demonstrated that coinciding (foreperiod and late) LRPs can under certain circumstances (Willemssen et al., 2004) be merged into a single compound. If then, for example, both waveforms activate opposite motor cortices, the resulting motor potential can be drastically reduced in terms of amplitude. Both these accounts of LRP amplitude reduction can be applied to the present data. It is possible that a smaller amplitude for late LRP in the one-back task reflects motor preparation, as well as it may be a compound of foreperiod and late motor potentials elicited in opposite hemispheres (i.e. when stimuli X and X-1 are different). In summary, the LRP onset and amplitude differences between the standard and the one-back choice RT task seem to reflect motor preparation in the one-back task. Nevertheless, we are not able to consolidate this presumption since a foreperiod LRP could not be identified. The motor potentials analyzed in the present study were averaged at the task-level and the statistical power of the design is too small for directly comparing the electrophysiological correlates associated with the different types of one-back choice RT task trials (e.g. trials where stimulus X activates the same vs. a different response compared to the X-1 response). In future experimental designs, direct manipulations at trial level will be necessary to improve our understanding of the time course of motor activation in the one-back choice RT task.

The observation that at task level, the amplitude of the N2 index of response conflict was comparable in the one-back choice RT task as in the standard choice RT task does not mean that conflict was not induced at all. First, in most conflict tasks (e.g. flanker task) conflict is only induced in a subset of the trials (e.g. incongruent flanker trials), by which it might not be detectable at general task level. Second, it would be unexpected that a response conflict does not occur in a one-back choice RT task where the processing of a stimulus X-1 is not yet finished at the time processing of a stimulus X is already engaged to a stage of response activation (see N2 amplification and

LRP onset differences in the present data). We further investigated this matter by conducting a post-hoc analysis of the one-back choice RT task at the level of the individual trials. In the one-back task, congruent and incongruent trials can be distinguished. A congruent trial occurs when stimulus X elicits the same response as stimulus X-1. Conversely, when stimulus X and stimulus X-1 require a different response, the trial on which stimulus X is presented will be incongruent. A post-hoc comparison (Tukey test) pointed towards a significant congruency effect of 48 msec on average ($p < .001$).

What do we conclude from this comparison at the level of individual trials? Reaction times in the one-back choice RT task are 48 msec slower for incongruent trials, i.e. when the response elicited by stimulus X is different compared to the response required for stimulus X-1, or in other words, when the stimulus identity alternates (when stimuli X-1 and X are different, trial X is always incongruent). In a further post-hoc comparison, we compared N2 amplitudes as a function of the trial types, but we found no reliable effects. However, the number of valid ERP epochs per type condition was low and the number of observations per condition was unevenly distributed over the conditions. Further experiments that directly manipulate trial type are needed in order to contrast N2 amplitudes for congruent and incongruent trials.

Interestingly, N2 amplitude was similar for both RT tasks and P3 amplitude differed, whereas both ERP measures are acknowledged measures of executive control. At first sight, these results might seem contradictory, but not when we take into account the fact that both ERP markers presumably do not reflect exactly the same underlying control mechanisms. The N2 has specifically been associated with cognitive conflict (especially response conflict) and inhibition, whereas the relation between P3 and executive control is more idiosyncratic (P3 reflects the consumption of executive resources in general). Like the present post-hoc analyses suggest, conflict does not occur at each one-back choice RT task trial, which can explain the present failure to detect an enhanced N2 at task level. What the P3 amplitude reduction in the one-back task suggests, is that the consumption of executive resources is possibly not limited to those trials at which cognitive conflict occurs. In the conflict literature, it has been demonstrated that in specific circumstances, executive control and conflict can be dissociated (Mayr, Awh, & Laurey, 2003). When a congruent trial X follows an incongruent trial X-1, top-down conflict adaptation has occurred at trial X-1 and subjects are under a state of high executive control when trial X is presented, even if X is not a conflict trial. Accordingly, trial X will be characterized by high executive control but low conflict (thus no N2 amplification) and at task level by consequence, conflict trials will be less numerous than trials for which executive control resources are deployed. Hence, it is possible that electrophysiological differences between the standard and the one-back choice RT tasks are more easy to detect on an ERP marker of executive resource deployment (i.e. P3) than on an index of cognitive conflict (i.e. the N2), as observed in the present study. It must be emphasized that these tentative conclusions are drawn on an exploratory basis; still we believe that they point towards the necessity to further explore the potential of the one-back choice RT task as a conflict task.

Finally, the conclusions of the present study can be summarized as follows. First, the reduced P3 amplitude for the one-back choice RT task compared to the standard choice RT task is consistent with the earlier behavioral finding that the one-back task involves more executive resources than the standard choice RT task. Second, the N2 data revealed that in the one-back choice RT task, stimulus X is processed to the stage of response activation (see effect of Perceptual Overlap on N2 amplitude) before the choice reaction to stimulus X-1 is terminated, a finding that is indirectly supported by the observation that the late LRP associated with the one-back task gives evidence of response preparation. This overlap between the cognitive processing of the successive stimuli X-1 and X was hypothesized to induce a response conflict, which we identified as a potential source of additional executive involvement in the one-back task. On the one hand, this hypothesis was not confirmed since at task level, the N2 marker of response conflict was comparable for both choice RT tasks. On the other hand, post-hoc analyses at trial level showed that incongruent one-back trials were processed slower than congruent ones, a finding that is analogous to the congruency effects observed in conflict tasks. The lack of clear effects on the N2 and LRP measures and the indications provided by the post-hoc congruency analysis suggest that further ERP investigation at the level of the individual trials is necessary in order to gain an insight into the cognitive processes involved in the one-back choice RT task and in order to explore its potentials as a new conflict task.

REFERENCES

Baddeley, A. D. (1986). *Working Memory*. Oxford: Oxford University Press, Clarendon Press.

Coles, M.G.H. (1989). Modern mind-brain reading: Psychophysiology, physiology, and cognition. *Psychophysiology, 26,* 251-269.

Doucet, C., & Stelmack, R.M. (1999). The effect of response execution on P3 latency, reaction time, and movement time. *Psychophysiology, 36,* 351-363.

Eriksen, B.A., & Eriksen, C.W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception and Psychophysics, 16*, 143-149.

Falkenstein, M., Hoormann, J., & Hohnsbein, J. (1999). ERP components in Go/Nogo tasks and their relation to inhibition. *Acta Psychologica, 101*, 267-291.

Fechner, G.T. (1860). *Elemente der Psychophysik*. Leipzig: Breitkopf und Härtel, 2, p. 559.

Joppich, G., Dauper, J., Dengler, R., Johannes, S., Rodriguez-Fornells, A., & Münte, T. F. (2004). Brain potentials index executive functions during random number generation. *Neuroscience Research, 49*, 157-164.

Kok, A. (2001). On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology, 38*, 557-577.

Leuthold, H., Sommer W., & Ulrich R. (1996). Partial advance information and response preparation: Inferences from the lateralized readiness potential. *Journal of Experimental Psychology: General, 125,* 307-323.

Liotti, M., Woldorff, M.G., Perez, R., & Mayberg, H.S. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia, 38*, 701-711.

MacLead, G.M. (1991). HaIf a century of research on the Stroop Effect: an integrative review. *Psychological Bulletin and Review, 109*, 163-203.

Mayr, U., Awh, E., & Laurey, P. (2003). Conflict adaptation effects in the absence of executive control. *Nature Neuroscience, 6,* 450-452.

Miller, J. O., & Hackley, S. A. (1992). Electrophysiological evidence for temporal overlap among contingent mental processes. *Journal of Experimental Psychology: General, 121,* 195-209.

Mordkoff, J.T., & Gianaros, P.J. (2000). Detecting the onset of the lateralized readiness potential: A comparison of available methods of procedures. *Psychophysiology, 37,* 347-360.

Muller-Gethmann, H., Rinkenauer, G., Stahl, J., & Ulrich R. (2000). Preparation of response force and movement direction: onset effects on the lateralized readiness potential. *Psychophysiology, 37,* 507-514.

Nieuwenhuis, S., Yeung, N., & Cohen, J.D. (2004). Stimulus modality, perceptual overlap, and the Go/No-Go N2. *Psychophysiology, 41*, 157-160.

Rosenbaum, D.A. (1980). Human movement initiation: Specification of arm, direction, and extent. *Journal of Experimental Psychology: General, 109,* 444-474.

Rosenbaum, D.A. (1983). The movement precuing technique: Assumptions, applications, and extensions. In R.A. Magill (Ed.), *Memory and control of action* (pp. 231-274). Amsterdam: Elsevier.

Stroop, J. R. (1935). Studies of inference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643-662.

Swainson, R., Cunnington, R., Jackson, G.M., Rorden, C., Peters, A.M., Morris, P.G., & Jackson, S.R. (2003). Cognitive control mechanisms revealed by Erp and Fmri: Evidence from repeated task-switching. *Journal of Cognitive Neuroscience, 15,* 785-799.

Ulrich R., Leuthold H., & Sommer W. (1998). Motor programming of response force and movement direction. *Psychophysiology, 35,* 34-46.

Wild-Wall, N., Sangals, J., Sommer, W. & Leuthold, H. (2003). Are fingers special? Evidence about movement programming and preparation from event-related brain potentials. *Psychophysiology, 40*, 7-16.

Willemssen, R., Hoormann, J., Hohnsbein, J., & Falkenstein, M. (2004). Central and parietal event-related lateralizations in a flanker task. *Psychophysiology, 41*, 762-771.

Yeung, N., Botvinick, M.M., & Cohen, J.D. (2004). The neural basis of error detection: Conflict monitoring and the error-related negativity. *Psychological Review, 111*, 931-959.

CHAPTER 6
GENERAL CONCLUSIONS

In this final chapter, I will first summarize the main findings that emerged from the present series of studies. Next, I will attempt to incorporate these findings into an integrative theory of executive control. Further, attention will be drawn to several points of interest that require some elaboration in the light of the theoretical formulations. The chapter is concluded with directions for future experimental research on executive control.

RESEARCH OVERVIEW

The point of departure of the present dissertation was the unsatisfactory theoretical and methodological situation in executive control research today (Rabbitt, 1997). As described in the general introduction, the concept of executive control is still poorly understood, the conventional measures of executive control are psychometrically inadequate and most essentially, there is a lack of paradigms to study executive control (Barnard, Scott, & May, 2001). The purpose of this dissertation was twofold. First, it was aimed to *meet the methodological shortcomings* by introducing a new method to study executive control within the working memory framework. The second objective was to apply the new method in order to *gain a theoretical insight* into the concept of executive control. This was done by addressing the research question whether executive control is a unitary system or whether it is rather a conglomerate of separable executive functions?

BEHAVIORAL STUDIES

In Chapter 2, we proposed to use the selective interference paradigm to investigate executive control within Baddeley's (1986) working memory framework. The idea was to operationalize a potential executive function by means of a so-called secondary task and to estimate the executive demands of this secondary task by investigating its pattern of interference with a number of primary tasks that tap the different subcomponents of working memory. The target executive function in Chapter 2 was *response selection*, a function that was quite recently proposed to involve executive control (e.g. Hegarty, Shah, & Miyake, 2000; Klauer & Stegmaier, 1997; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000). Response selection was made operational by means of an auditory choice RT task. The executive involvement in response selection was measured by comparing the dual-task effects of the choice RT task and a control task that does not involve response selection (i.e. a simple RT task; Schubert, 1999), on primary tasks that require executive, verbal and visuospatial processing. In addition, the patterns of dual-task impairment of the simple and the choice RT task were compared to the interference of secondary tasks which are known to selectively interfere with the working memory slave systems (i.e. articulatory suppression for the Phonological Loop and matrix tapping for the Visuospatial Sketchpad). The results showed that the choice RT task interfered more with a primary task that involves executive control (i.e. verbal fluency), than the simple RT task. In addition we observed that when the executive demands of the primary task were augmented and the verbal demands were kept equal (backward versus forward verbal serial recall), the dual-task effects of the choice RT task on the primary task increased while the interference due to articulatory suppression remained similar. Finally, when the executive demands of the primary task were held constant and the visuospatial involvement was manipulated (forward versus backward visuospatial serial recall), the primary task impairment due to the choice RT task did not change whereas the interference of matrix tapping did. Together, these results show that (1) the choice RT task, compared to the simple RT task, causes additional interference with executively demanding primary tasks, (2) the choice RT task gives evidence of a pattern of dual-task interference that is typical for secondary tasks that selectively interfere with executive control and (3) the patterns of impairment associated with secondary tasks that selectively interfere with verbal and visuospatial processing can be dissociated from the dual-task interference observed with the choice RT task. Therefore, we concluded that the choice RT task is a relatively selective source of interference with executive control in the sense that the interference is not mediated at the level of working memory's slave systems. We interpreted this as supportive evidence for the position that response selection involves executive control.

How does Chapter 2 contribute to the research goals of this dissertation? First, it provides a method for studying executive control within Baddeley's (1986) working memory framework. The method operationalizes an alleged executive function and it offers a tool to (1) measure the magnitude of the executive involvement and (2) examine whether the effects of the hypothesized executive function can be dissociated from effects achieved at the level of the slave systems. Second, Chapter 2 indicates that the method can be applied to explore the fractionability of executive control. As outlined in the introduction, there is a tendency to redefine the Central Executive as an aggregate of related executive functions (Baddeley, 1996; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). In this vein, we demonstrated that executive involvement is already detectable at a rather basic level of cognitive processing, which is response selection. Importantly, based on the observation that response selection is involved in nearly all tasks that measure the conventional executive functions, this suggests that functions such as updating, inhibition or switching are probably not the basic units of executive control, since they seem to be fractionable into even more basic elements, like response selection for example. Third, while task impurity has since long been a major problem in executive function research, the study reported in Chapter 2 yielded an executively demanding task that does not put an important load on the slave systems, namely the choice RT task with auditory signals. This particular task has been used in a number of recent studies, both as an operationalization of response selection (e.g.

Deschuyteneer & Vandierendonck, in press), and as a not further specified executively demanding task (e.g. De Houwer & Beckers, 2003).

The research method which was validated in Chapter 2 was further applied in Chapter 3 to estimate the executive demands of a task manipulation that has not been investigated before. It concerns the requirement to delay a choice reaction until the presentation of the subsequent stimulus, which we represented by means of the one-back choice RT task. Based on the theoretical similarities between the one-back choice RT task and the *n*-back procedure which is generally assumed to involve the executive function of updating (Morris & Jones, 1990), it was proposed that the one-back choice RT task also operationalizes *updating*. Accordingly, assuming that the one-back choice RT task involves updating whereas a standard choice RT task does not, we hypothesized that the one-back task involves more executive control than a standard choice RT task. This hypothesis was tested by formulating the same predictions and following the same experimental rationale as in Chapter 2. The results showed that the one-back choice RT task, compared to the standard choice RT task, interfered more with primary tasks that require executive control. Furthermore, it was demonstrated that the additional interference of the one-back choice RT task was not achieved at the level of the Phonological Loop or the Visuospatial Sketchpad. On the basis of these findings, we concluded that the requirement to delay a choice reaction until the onset of the next stimulus is an executively demanding operation.

What does the latter conclusion tell about underlying executive processes? Based on the theoretical position that the one-back choice RT task involves the active maintenance of information and the updating of this information each time a new trial is presented (i.e. the definition of updating according to Morris & Jones, 1990), one could be prudent and conclude that the results of Chapter 3 support the position that updating is involved in a one-back choice RT task. However, one could go further. More precisely, starting from the Morris and Jones definition of updating, it is theoretically sound to assume that updating is involved in the one-back task. Hence, the observation that the one-back task is more executively demanding than a standard choice RT task, could lead towards the conclusion that updating is an executive function and that the one-back choice RT task is an operationalization of the updating function that does not load importantly on the slave systems. I believe that, although they are somewhat circular, both aforementioned conclusions are acceptable in the domain of executive control research today, provided that their hypothetical nature (with respect to the assumption that updating is involved) is acknowledged. As put forward in the discussion of Chapter 3, I remain doubtful about whether we need the executive concept of updating to provide an interpretation of the observed findings. In what follows, I will go more deeply into this point of discussion.

The central point of my argument is the distinction between *task demand* and *cognitive process*. Task demands and the underlying cognitive processes are not mapped one-to-one. This makes it difficult to draw straightforward conclusions when task manipulations are interpreted at the processing level. In this view, the only legitimate conclusion that can be drawn from the study presented in Chapter 3 is that the task instruction to delay a response until the occurrence of the following stimulus selectively taxes executive resources. Similarly, the only straightforward conclusion to be drawn from Chapter 2 is that making a choice reaction taxes more executive resources than making a simple reaction. Any further conclusions on the cognitive processes that underlie these task demands remain hypothetical. Which cognitive process(es) make(s) a choice RT task more executively demanding than a simple RT task? It may be response selection, but it could equally well be a process that is related to the stimulus classification phase. And what makes a one-back choice RT task more executively demanding than a standard choice RT task? Is it the process of updating or is it rather a cognitive conflict that arises from the fact that in a one-back task, stimulus X+1 is already presented before the choice reaction to stimulus X is finished (cfr. Chapter 5). By consequence, also the main question remained unanswered: are the response selection task and the updating task operationalizations of two different executive processes or should they be understood as two different tasks that tap a common executive control mechanism? It is with this kind of questions that we were left, when the studies presented in Chapters 2 and 3 were terminated. In this sense, the behavioral studies yielded a new method to investigate executive control as well as two relatively pure measures of executive control, i.e. the choice RT task and the one-back choice RT task, but the relation between those two tasks and the two hypothesized executive functions of response selection and updating, remained unclear. In this vein, the contribution of the behavioral studies was mainly methodological but the theoretical issues were not solved.

ELECTROPHYSIOLOGICAL STUDIES

In answer to the problems raised above, the response selection task and the updating task were further investigated by means of a method which makes it possible to measure task performance at the processing level (Chapters 4 and 5). To this end, the Event Related Potentials paradigm was used. Event related brain potentials are widely supported as an appropriate tool to index the brain activity that underlies cognitive processing. The ERP paradigm was applied in Chapter 4 in order to study the neural basis of the cognitive processes involved in the response selection task. Based on the perceptual overlap/response conflict theory of Nieuwenhuis, Yeung and Cohen (2004), we hypothesized that the executive demands of a choice RT task are related to the intensity of a response conflict that is a function of the degree of perceptual overlap between the stimuli (i.e. the discriminability of the auditory signals). Accordingly an experiment was designed in which participants performed a simple RT task and a choice RT task under three conditions of perceptual overlap (hard, intermediate and easy discriminability). The effects of this manipulation were investigated on the N2 component of the ERP. The N2 is a negative deflection of the fronto-parietal brain potential that is assumed to reflect activity from the Anterior

Cingulate Cortex (ACC). Although there has been some debate about whether the N2 specifically reflects response conflict or inhibition (e.g. Bruin, Wijers, & van Staveren, 2001), it is nowadays mainly recognized as an ERP marker of response conflict. Based on the aforementioned hypothesis, we predicted that response conflict - and thus the N2 – would be larger in a choice RT task than in a simple RT task, because in the latter task, all stimuli lead towards the same response and by consequence no response conflict is expected to occur. Second, assuming that response conflict in the choice RT task is a function of the discriminability among the stimuli, we predicted that N2 amplitude would increase with perceptual overlap in the choice RT task. The results showed a clear N2 in the choice RT task whereas in the simple RT task no N2 occurred at all. Regarding the perceptual overlap manipulation, the findings indicated that for the choice RT task N2 magnitude was larger in the condition with hard stimulus discriminability compared to the conditions with intermediate and easy discriminability. These results were explained as follows. When a stimulus is presented in a choice RT task, not only the correct response alternative is activated but also the incorrect response. The activation of the erroneous response seems to depend on the degree of perceptual overlap between the response alternatives. When, in a two-choice RT task for example, the stimulus alternatives (e.g. a high and a low tone) are perceptually resembling, also the incorrect response is highly activated when a stimulus occurs, through which a situation of high response conflict is induced (as evidenced by N2 amplification). Conversely, when both stimulus alternatives are easy to discriminate, the incorrect response is less activated and by consequence also the response conflict is smaller (and N2 amplitude is reduced). In a response conflict situation, executive control can be understood as a top-down regulation from the central task goal representation to the level of response activation which must ensure that the incorrect response alternative is inhibited so that the correct response can be executed. In a simple RT task, however, participants are required always to make the same response, irrespective of the identity of the stimulus. This implies that there is only one response alternative and by consequence, a response conflict situation is not expected, as evidenced by the finding that no N2 occurs.

In Chapter 5, we carried out a similar ERP experiment to investigate the cognitive processing underlying performance on the one-back choice RT task, our hypothesized measure of the executive function of updating. The nature of this study was more explorative in the sense that, contrary to Chapter 4, no explicit predictions were formulated about the neural basis of executive involvement in the one-back choice RT task. The main goal of the study was to understand how the one-back choice RT task is completed and more specifically to address the question whether stimuli in the one-back task are instantly processed or whether their cognitive processing is delayed until the choice reaction to the previous stimulus is terminated. The specific matter of potential sources of additional executive involvement in the one-back compared to the standard choice RT task was addressed post-hoc. The main results of the study presented in Chapter 5 can be summarized as follows. First, the findings of Chapter 4, regarding the N2 amplification with increasing perceptual overlap (in the standard choice RT task), were replicated. Second, the same N2 amplification was observed in the one-back choice RT task. Given that the N2 is assumed to reflect response conflict, the latter finding suggests that, although a newly presented stimulus is in essence a trigger for executing the response to the previous stimulus (one-back), it is still instantly processed until the stage of response activation. Third, the data revealed that one-back choice RT task trials on which the response elicited by (trigger) stimulus X+1 is different from the response to stimulus X (i.e. incongruent trials), are processed slower than trials on which both stimulus X and X+1 require the same response (i.e. congruent trials). On the one hand, this corroborates the finding that stimulus X+1 is instantly processed (cfr. N2 data). On the other hand, it shows that interference occurs between the processing of subsequent stimuli. This interference is a potential source of conflict, in the form of competition between the response to stimulus X and the response to stimulus X+1, a situation were ACC is typically engaged. The potentials of the one-back choice RT task as a conflict task can be elaborated by investigating the congruency effect at the level of N2 amplitude. This could not be realized on the basis of the experimental design presented in Chapter 5 but it is nevertheless something that deserves further attention.

The neurophysiological studies suggest that the neural basis of executive involvement in the response selection task is reflected in the N2 component (Chapter 4), which is not present in a task that does not involve response selection and which varies in terms of amplitude as a function of response conflict (as induced by the degree of perceptual overlap between alternative stimuli). The conclusions regarding the updating task (Chapter 5) are more speculative but seem to suggest that (part of) the executive involvement in the one-back choice RT task may be related to a cognitive conflict between successive trials. Interestingly, the N2 component has also been associated with other executive functions like inhibition (e.g. Bruin et al., 2001) or task switching (e.g. Swainson, Cunnington, Jackson, Rorden, Peters, Morris, et al., 2003). In the inhibition literature, virtually any task that requires the overriding of a prepotent response involves N2 amplification (Stroop task, Flanker task, the Go/Nogo paradigm, the global-local paradigm). This N2 amplification is generally accounted for by a conflict between the correct response and the one being overridden. In the domain of task switching, it is a replicated finding that N2 amplitude is larger for switch (i.e. task alternation) than for nonswitch trials (i.e. task repetition). It has been demonstrated that both the classical switch cost as well as the residual switch cost (a cost that remains despite endogenous or voluntary preparation; Rogers & Monsell, 1995) are associated with a N2 amplification. Also in the task switching paradigm, these N2 findings are attributed to a response conflict. When a person switches from one task to another, a competition arises between the correct response and the response that applied to the previous task, and top-down regulation is involved in order to actively suppress the inappropriate response (Swainson et al., 2003).

The main conclusion that can be drawn from the electrophysiological part of this dissertation is that most of the task manipulations that are supposed to tax a hypothesized executive function produce an increase in the amplitude of the N2. This conclusion counts for the presumed executive functions of inhibition and task switching and, on the basis of the current findings, also for response selection (and possibly updating). In addition, an unpublished manuscript by Vandromme (2003) indicates that the conclusion may also be applied to the executive function of dual-tasking since it was demonstrated that N2 amplitude in a choice RT task is higher under dual-task (i.e. concurrently with verbal serial recall) than under single-task conditions. Therefore, we conclude that neural activity at the level of the ACC (which can be inferred from N2 amplitude) provides a neural basis for a large number of the often postulated executive functions.

AN INTEGRATIVE THEORY OF EXECUTIVE CONTROL

Starting from the Central Executive component of working memory, the initial goal of this dissertation was to demonstrate that executive control is not a unitary system but merely a generic term for a set of independent but interacting executive functions. It is from this perspective that the experiments described in Chapter 2 were interpreted. The study reported in Chapter 3 clearly demonstrated that the task instruction to delay a choice reaction until the onset of the next stimulus demands additional executive resources. This does however not necessarily imply that another executive function is involved as well. At that point, some concerns were expressed about what is really being fractionated: executive task demands or executive processes. The latter possibility was somehow weakened by the ERP studies, which suggest that a common mechanism, which manifests itself in the N2 component of the ERP, underlies performance on a range of so-called executive tasks. Today, I remain doubtful, not only about the idea that executive control is a unitary system but also about the position that switching, updating, inhibition, response selection … are separable executive functions.

Accordingly, in this second part of the general conclusions, I attempt to formulate a tentative integrative theory of executive control which I presume can account for a majority of the findings in executive control research today. I would like to stress that this theoretical account is not restricted to the findings presented in this dissertation. The reason is that the empirical part of this dissertation does not deal with a number of issues that are of importance in executive control research today and that by consequence should be incorporated in an integrative account of executive control (e.g. the role of the Dorsolateral Prefrontal Cortex in executive control). In this vein, the following theoretical position is based on the broad executive control literature, amongst which also the present empirical contributions.

As I mentioned before, executive control is probably neither a unitary mechanism, nor is it a conglomeration of four or five separable executive functions. An inspection of the relevant literature indicates that during the last decade, only two executive control mechanisms have clearly been identified and dissociated, namely one serving an *active maintenance* function and another serving a *monitoring* function. In the next paragraphs, both mechanisms will be described in more detail and I will argue that these two mechanisms suffice to integrate current working memory, neurophysiological and the neuroimaging views on executive control.

As explained in the introduction, the effectiveness of executively controlled behavior is associated with the capacity to keep active a task-goal and the means to achieve that goal. It is assumed that these goals and rules are maintained in working memory, through which working memory is attributed a crucial role in executive control. Over the years, several neuroimaging studies have tried to find out where in the brain this task relevant information is kept active, or in other words, which areas of the brain serve executive control in working memory (Smith & Jonides, 1997;

1999; Van der Linden, Collette, Salmon, Delfiore, Degueldre, Luxen et al., 1999). Several executive control tasks have been used in these studies, each presumed to tap on a particular executive function. Interestingly, despite the fact that those tasks were presumed to operationalize different executive functions, they were mostly demonstrated to activate a common brain area, namely the Dorsolateral Prefrontal Cortex (DLPFC). Based on these findings, the view has developed that DLPFC serves a specific function in executive control: the active maintenance of task goals and task rules (see Miller & Cohen, 2001). According to Miller & Cohen (2001), this active maintenance should be understood as a pattern of neural activity that biases activation along the neural pathways leading to appropriate action. These authors argued that the postulated executive functions “depend on the representation of goals and rules in the form of patterns of activity in the PFC, which configure processing in other parts of the brain in accordance with current task requirements” (Miller & Cohen, 2001, p. 170). Therefore, demands for control are associated with an increase in DLPFC activity, as usually observed in brain imagery literature (Smith & Jonides, 1999). It is assumed that by way of biasing activation, DLPFC has a top-down regulative effect on lower level cognitive processes, so that purposeful action is taken. Whereas DLPFC is believed to be primarily a regulative device (perform adjustments in executive control by way of altering patterns of activation) it is assumed not to have the capacity to evaluate when the need for top-down regulation occurs. As outlined in the next paragraph, this evaluative function is rather attributed to a monitoring system that resides in the Anterior Cingulate Cortex (ACC).

The main hypothesis concerning the ACC is that it functions to signal the occurrence of conflict (mainly response conflict) in information processing (Botvinick, Cohen, & Carter, 2004), thereby triggering adjustments in executive control, the latter being the function of the DLPFC as described before. The conflict monitoring hypothesis is grounded on a wealth of evidence for ACC activation in tasks that require the overriding of prepotent responses (the so-called conflict tasks). Furthermore, ACC activation has also been associated with the commission of errors and with underdetermined responding (i.e. a context of competition between permissible responses), two settings in which involvement of ACC is also explained based on a single function, namely the detection of response conflict (Barch, Braver, Akbudak, Contoro, Ollinger, & Snyder, 2001). More recently however, it has been suggested that ACC is involved in a broader context of monitoring and evaluating the outcomes of action and that conflict is merely one of the outcomes to which the ACC is sensitive. This position is based on a number of phenomena that trigger ACC activation but that are not plausibly interpretable in terms of response conflict detection (e.g. gambling, reward expectation). By consequence, the conflict monitoring hypothesis is now preferably seen as a specific case of the broader outcome evaluation account of ACC functioning (Botvinick et al., 2004).

In summary, we propose that executively controlled behavior is produced by both the capacity to maintain a task-goal active and the capacity to detect a possible mismatch between the task-goal and the actual outcome of behavior. When a goal is not satisfactorily met, the monitoring function signals the active maintenance mechanism which is able to shift attention or strengthen top-down control in the form of biasing the appropriate patterns of neural activation towards lower level processes (top-down). Also computational modeling work has demonstrated that coupling outcome evaluation to compensatory adjustment can accurately simulate participants' behavior in executive tasks (e.g. Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). Next, I will attempt to clarify how the active maintenance - monitoring theory can account for the findings described in this dissertation.

The task-goal and particularly the means to achieve that goal are more complex in a choice RT task than in a simple RT task. The choice RT task imposes higher demands on stimulus evaluation and response selection[1] and also the stimulus-response translation rules are more complicated. In addition, the specific stimulus-response translation rules that were used in the present studies (push right for high tone, left for low tone) are arbitrary which suggest that they are more controlled than more natural (or automated) rules (e.g. push right for an arrow that points to the right). This suggests that DLPFC, the brain area where the goals and rules for the choice RT task are maintained active (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Rowe et al., 2000), will exert stronger neural activation bias (arbitrary translation rules) and also activation bias towards brain regions that are not involved in the simple RT task (e.g. for stimulus discrimination or response selection). Accordingly, a stronger DLPFC activation pattern is expected in the choice RT task or to put it differently, the choice RT task is anticipated to be more executively demanding than a simple RT task (which was observed in Chapter 2). Then, while participants are performing the choice RT task, left and right responses alternate in an unpredictable order, and when a new stimulus is presented, both response alternatives are activated. The ACC detects the undesired activation (Chapter 4) and signals the top-down control mechanism (in DLPFC) in order to adjust the patterns of response activation conform to the task requirement.

The results of Chapter 3 demonstrated that the one-back choice RT task in turn involves more executive control than the standard choice RT task. In a majority of real life situations and in any capacity assessment context,

---

[1] This does of course not mean that stimulus evaluation or response selection as such occurs in DLPFC, nor that specific stimulus or response information (e.g. perceptual characteristics) is represented in this brain region; it rather suggest that DLPFC “knows” that part of the task is to categorize a stimulus and to select a response, which is reflected by an activation bias towards the brain areas that serve these specific processes.

people are used to provide a response as soon as it is available. In the context of the one-back task however, participants are required to delay a response until the following trial. It is likely that such an unconventional task demand is not applied automatically and that it must be maintained active in DLPFC, which can explain the additional executive demands of the one-back task. In addition, the results of Chapter 5 suggest that the one-back choice RT task involves a competition between the response to stimulus X and the response elicited by stimulus X+1, which is a potential locus of ACC involvement in the one-back task and by consequence, a possible source of additional top-down regulation at the level of DLPFC, which might also account for the additional executive demands observed in Chapter 3.

One aim of this doctoral dissertation was to take a position in the debate on unity versus diversity within executive control. Although, as I described earlier, this position has evolved throughout the course of the present work, it should be clear from the integrative theoretical account that the active maintenance/monitoring theory assumes that the classical executive functions depend on the representations of goals and rules in the form of patterns of activity in the DLPFC. This is supported by the observation that virtually any task manipulation that operationalizes a hypothesized executive function, is associated with activation in the DLPFC. Analogously, the need for adaptation of control is in nearly all executive tasks signaled by the ACC. This shows that the often postulated executive functions share a common neural basis, which favors the view that these presumed executive functions can be seen as task demands that are met by a common executive control system. But there is more evidence which suggests that it might be acceptable to define executive involvement at the task level rather than at the level of individual processes.

Take response selection for example. A number of studies have suggested that response selection is an executive function, based on the observation that a choice RT task involves executive control (Chapter 2; Klauer & Stegmaier, 1997). However, the flanker paradigm makes an assumption that somewhat concurs with this idea. In essence, the Eriksen flanker task (Eriksen & Eriksen, 1974) is a choice RT task with arrows (left/right selection as a function of left/right pointing arrow) in which the target arrow is flanked by arrows pointing either in the same (i.e. congruent trial) or in a the different direction (i.e. incongruent trial). It is typically observed that incongruent flanker trials are processed slower than the congruent ones, a finding which is referred to as the flanker effect. In order to explain this effect, it is assumed that the flanking stimuli are processed automatically; even to the stage of response activation (flankers elicit an LRP; Willemssen, Hoormann, Hohnsbein, & Falkenstein, 2004).

The assumption that a two-choice reaction occurs automatically in the Eriksen flanker paradigm, while it appears to be controlled in other circumstances, points towards the importance of the task context. Therefore, it may be preferable to consider executive involvement at the task level than at the level of individual processes. In fact, this is quite consistent with what Allain, Carbonnell, Burle, Hasbroucq and Vidal (2004) observed in an electromyographic (EMG) study of executive involvement in a choice RT task. They reported that EMG indicators of executive involvement were activated throughout a choice RT task trial and that this activation declined after the response was executed. This suggests that executive control does not supervise one discrete stage of the choice RT task but that it rather continuously monitors performance until the response has been given. Therefore, Allain et al. concluded that a choice RT task involves executive control, which is in the light of the present discussion not the same as saying that response selection is an executive function. This can also explain why the idea of executive involvement in a relatively basic process as response selection has been an issue of controversy. Several researchers have doubts about it because indeed, there are clearly contexts in which response selection is more automated than in others[2]. When it comes to integrating both areas of evidence in order to gain a theoretical insight into the concept of executive control, I now believe that it is more plausible to shift the locus of executive involvement from the process level to the task level and assume that some tasks might require that response selection is executively controlled (rather than saying that response selection is an executive function in some circumstances). Note that this line of reasoning can be applied to other executive functions as well. During task switching for example, it has been argued that the inhibition of the previous task-set occurs more automatically than the inhibition of erroneously activated responses during incongruent (i.e. when both the task and the required response alternate) switch trials (e.g. Koch, Gade, & Phillip, 2004).

With respect to the outcome evaluation (in ACC) and the active maintenance functions (in DLPFC), a number of studies involving the Stroop and the flanker tasks have provided compelling evidence for a dissociation between those functions (e.g. MacDonald, Cohen, Stenger, & Carter, 2000). These studies demonstrated that high-conflict/low-control trials (i.e. high ACC activation, low DLPFC activation) can be differentiated from low-conflict/high control trials (i.e. low ACC activation, high DLPFC activation). The first situation usually occurs when an incongruent flanker or Stroop trial follows a series of congruent trials, the latter especially when an incongruent trial is preceded by a series of incongruent trials. By contrast, regarding the several postulated executive functions, it has proven particularly difficult to find dissociations, by which the unity versus diversity debate is still going. Also in the present dissertation, the patterns of dual-task interference that were observed with the response selection task and the updating task were not dissociated. As I mentioned in the introduction, a number of correlational approaches have addressed the issue

---

[2] As explained before, this might be due task properties like the physical properties of the stimuli, the number of choice alternatives or the extent to which the stimulus-response mappings are unusual, for example.

(Lehto, 1996; Miyake et al., 2000) and although the results of this studies have predominantly been interpreted in favor of the diversity position, I believe that they can equally well be explained by the position that has been taken in the present conclusions. What would one expect from a correlational analysis of performance on an *n*-back updating task and a stop-signal inhibition task? I would predict moderate correlation because even if both tasks might have a common executive basis, non-executive, task-specific differences (such as stimulus material or response modalities) can still distort the common variance; and moderate correlations are in fact mainly found.

There is one potential drawback of reducing executive functions to differences in task demands met by common executive control mechanisms. If for example, the difference in executive demands between a one-back choice RT task and choice RT task can not be explained in terms of qualitative processing differences (i.e. updating), one might argue that the risk for confounding executive demands with *task difficulty* becomes eminent. Moreover, the findings of Barch, Braver, Nystrom, Forman, Noll and Cohen (1997) who showed that task difficulty increases ACC activity, underline the pertinence of this concern. Therefore, in the final point of this section, some attention will be given to the issue of task difficulty. To this day, an important number of researchers believe that, even when variations in task difficulty can be accounted for by differences in processing demands, task difficulty remains a potentially confounding variable. In this debate, I adhere to the view that it is crucial to know which cognitive processes cause additional task difficulty but once these are known, task difficulty becomes merely a descriptor of a manipulation's consequence (Garavan, Ross, Li, & Stein, 2000). By contrast, the position that task difficulty can be confounded with cognitive demands (whatever their nature) does assume that both are separable variables and thus that task difficulty has more than a descriptive function. However, it does not seem plausible that the cognitive demands of a task can be increased without altering the difficulty of a task and similarly, that the difficulty of a task can be increased without appealing on some specific cognitive demand. In other words, task difficulty and cognitive demand do not seem dissociable, which is a serious challenge to the notion of confounding factors. Therefore, I agree with Botvinick et al. (2004) that the induction of cognitive demands like conflict monitoring or top-down control can be considered to be a defining feature of difficult tasks.

FUTURE DIRECTIONS

In the final part of this concluding chapter, a number of directions for future investigation are presented. In the preceding conclusions, I have expressed a preference for the position that the concept of executive control involves an evaluative (outcome evaluation) and a regulative (top-down control) function and that the conventional executive functions can be seen as different task requirements that are met by applying these evaluation and regulation mechanisms. In this view, although there might be several tasks (updating, inhibition, switching tasks) available to measure executive control capacities, the different tasks are in essence assumed to measure the same evaluative and regulative executive capacities. This position is principally based on the observation that the conventional executive functions share a common neural basis (DLPFC and ACC), that these functions are apparently not always executively controlled and that, contrary to the regulation and evaluation mechanisms, no conclusive evidence has been found for dissociation among executive functions. In this vein, I think that the potential to dissociate among the hypothesized executive functions must be more thoroughly elaborated because this is probably a most crucial but to this day still undetermined source of information for the unity versus diversity debate. One requirement will be to have valid and reliable measures of the often postulated executive functions, for which the new strategy presented in this dissertation may be helpful.

A second future direction is related to the specific role of working memory in executive control. It is assumed that working memory maintains the task-goal and the belonging rules active during controlled processing. Quite recently, it has been suggested that also verbal working memory is involved in the presumed executive function of task switching. More precisely, Emerson and Miyake (2003) argued that verbal working memory (by means of inner speech) plays a supportive role during task switching, in the sense that it holds a phonological representation of the upcoming task. This seems to suggest that the high demands put on the limited capacity executive control system can somehow be relieved by holding active a verbal representation of the task-goal (see also Liefooghe, Vandierendonck, Muyllaert, Verbruggen, & Vanneste, in press). I think that it is interesting to see how in the context of task switching, the Central Executive (or maybe the Episodic Buffer) can be assisted by the Phonological Loop in keeping the task-goal active and in the context of examining the functional diversity within executive control, I believe it would be worth while investigating whether also the other postulated executive functions can benefit from such verbal support.

Furthermore, with respect to the Episodic Buffer, it seems to me that Baddeley's working memory model has benefited from the inclusion of a multimodal maintenance system. The reason is that many researchers believe that working memory still serves a maintenance function in executive control (for the task-goals and rules; Miller & Cohen, 2001), whereas the Central Executive is not conceived of as maintenance system and the Episodic Buffer conversely is. The definition of the Episodic Buffer has not been made operational yet, but I believe that its role in executive control requires more attention in order to keep working memory's notion of executive control up to date. Finally, given the growing body of evidence for dissociation between a regulative and evaluative function in executive control research, it can be plausible to consider that the working memory component responsible for executive control by way of active maintenance and top-down regulation, is assisted by a component that is specialized in outcome evaluation.

REFERENCES

Allain, S., Carbonnell, L., Burle, B., Hasbroucq, T., & Vidal, F. (2004). On-line executive control: An electromyographic study. *Psychophysiology, 41*, 113-116.

Baddeley, A. D. (1986). *Working Memory*. Oxford: Oxford University Press, Clarendon Press.

Baddeley, A. D. (1996). Exploring the Central Executive. *Quarterly Journal of Experimental Psychology, 49A*, 5-28.

Barch, D.M., Braver, T.S., Akbudak, E., Conturo, T., Ollinger, J., & Snyder, A. (2001). Anterior cingulate cortex and response conflict: effects of response modality and processing domain. *Cerebral Cortex, 11,* 837-848.

Barch, D.M., Braver, T.S., Nystrom, L.E., Forman, S.D., Noll, D.C., & Cohen, J.D. (1997). Dissociating working memory from task difficulty in human prefrontal cortex. *Neuropsychologia, 35*, 1373-1380.

Barnard, P. J., Scott, S. K., & May, J. (2001). When the Central Executive lets us down: Schemas, attention, and load in a generative working memory task. *Memory, 9*, 209-221.

Botvinick, M.M., Cohen, J.D., & Carter, C.S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences*, *8*, 639-646.

Botvinick, M., Nystrom, L., Fissell, K., Carter, C., & Cohen, J.D. (1999). Conflict monitoring vs. selection-for-action in anterior cingulate cortex. *Nature, 402*, 179-181.

Bruin, K.J., Wijers, A.A., & Van Staveren, A.S.J. (2001). Response priming in a Go/Nogo task: Do we have to explain the Go/Nogo N2 effect in terms of response activation instead of inhibition? *Clinical Neurophysiology, 112*, 1660-1671.

Bunge, S. A., Hazeltine, E., Scanlon, M. D., Rosen, A. C., & Gabrieli, J. D. (2002). Dissociable contributions of prefrontal and parietal cortices to response selection. *Neuroimage, 17*, 1562-71.

De Houwer, J., & Beckers, T. (2003). Secondary task difficulty modulates forward blocking in human contingency learning. *Quarterly Journal of Experimental Psychology, 56B*, 345-357.

Deschuyteneer, M. & Vandierendonck, A. (in press). Are 'input monitoring' and 'response selection' involved in solving simple mental arithmetical sums? *European Journal of Cognitive Psychology.*

Emerson, M. J., & Miyake, A. (2003). The role of inner speech in task switching: A dual-task investigation. *Journal of Memory and Language, 48,* 148-168.

Eriksen, B.A., & Eriksen, C.W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception and Psychophysics, 16*, 143-149.

Garavan, H., Ross, T. J., Li, S. J., & Stein, E. A. (2000). A parametric manipulation of central executive functioning. *Cerebral Cortex, 10*, 585-592.

Hegarty, M., Shah, P., & Miyake, A. (2000). Constraints on using the dual-task methodology to specify the degree of central executive involvement in cognitive tasks. *Memory & Cognition, 28*, 376-385.

Klauer, K. C., & Stegmaier, R. (1997). Interference in immediate spatial memory: Shifts of spatial attention or central-executive involvement? *Quarterly Journal of Experimental Psychology, 50A*, 79-99.

Koch, I., Gade, M., & Philipp, A. M. (2004). Inhibition of response mode in task switching. *Experimental Psychology, 51*, 52-58.

Lehto, J. (1996). Are executive functioning tests dependent upon Working Memory capacity? *Quarterly Journal of Experimental Psychology, 49A*, 29-51.

Liefooghe, B., Vandierendonck, A., Muyllaert, I., Verbruggen, F., & Vanneste, W. (in press). The phonological loop in task alternation and task repetition. *Memory.*

MacDonald, A.W., Cohen, J.D., Stenger, V.A., & Carter, C.S. (2000). Dissociating the role of dorsolateral prefrontal cortex and anterior cingulate cortex in cognitive control. *Science, 288*, 1835-1837.

Miller, E.K. & Cohen, J.D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167-202.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49-100.

Morris, N., & Jones, D. M. (1990). Memory updating in working memory: The role of the central executive. *British Journal of Psychology, 81*, 111-121.

Nieuwenhuis, S., Yeung, N., & Cohen, J.D. (2004). Stimulus modality, perceptual overlap, and the Go/No-Go N2. *Psychophysiology, 41*, 157-160.

Rabbitt, P. (1997). *Methodology of frontal and executive function*. Hove, UK: Psychology Press.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictible switch between simple cognitive tasks*. Journal of Experimental Psychology: General, 124,* 207-231.

Rowe, J. B., Toni, I., Josephs, O., Frackowiak, R. S. J., & Passingham, R. E. (2000). The prefrontal cortex: Response selection or maintenance within working memory? *Science, 288*, 1656-1660.

Schubert, T. (1999). Processing differences between simple and choice reactions affect bottleneck localization in overlapping tasks. *Journal of Experimental Psychology: Human Perception & Performance, 25*, 408-425.

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology, 33*, 5-42.

Smith, E. E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science, 283*, 1657-1661.

Swainson, R., Cunnington, R., Jackson, G.M., Rorden, C., Peters, A.M., Morris, P.G., & Jackson, S.R. (2003). Cognitive control mechanisms revealed by Erp and Fmri: Evidence from repeated task-switching. *Journal of Cognitive Neuroscience, 15*, 785-799.

Van der Linden, M., Collette, F., Salmon, E., Delfiore, G., Degueldre, C., Luxen, A., & Franck, G. (1999). The neural correlates of updating information in verbal working memory. *Memory, 7,* 549-560.

Vandromme, H. (2003). The neurophysiological basis of dual-tasking by means of ERP. *Unpublished internship report.*

Willemssen, R., Hoormann, J., Hohnsbein, J., & Falkenstein, M. (2004). Central and parietal event-related lateralizations in a flanker task. *Psychophysiology, 41*, 762-771.