A comparison of behavioural and functional neuroanatomical correlates of executive functions in multitasking and working memory

A thesis submitted for the degree of Doctor of Philosophy

by

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Declaration

I hereby declare that this thesis has not been, and will not be submitted, in whole or in part to another University for the award of any other degree. Several experiments (Exp1b, 2c, 2e and 3) presented in this thesis are in preparation to be submitted to the following journal:

Otermans, P.C.J., Parton A, Szameitat A.J., (2018). The working memory costs of a central attentional bottleneck in multitasking. *Journal of Experimental Psychology: Human, Perception and Performance. In preparation.*

Otermans, P.C.J., Szameitat A.J. (2018). The central attentional bottleneck demands executive functions of working memory; a fMRI study. *NeuroImage. In preparation.*

Abstract

This thesis aims to explore the role of executive functions in multitasking. Research has shown that severe performance decrements often arise in dual-task performance, also called multitasking, as compared to single task performance. This reflects a limitation in processing temporally overlapping information. Interference between tasks arises due to a bottleneck process limited to processing only one task at a time. It has been proposed that this interference is resolved by executive functions. However, the dual-task paradigm employed in this thesis, Psychological Refractory Period (PRP) paradigm, (Pashler, 1994) is typically investigated in the field of human action performance, and the exact concept of executive functions remains underspecified.

However, while underspecified in the area of action performance, executive functions have been investigated in detail in the field of memory research, more specifically in the context of working memory (WM). Therefore, the aim of this thesis was to investigate whether the executive functions in PRP are related to the executive functions as discussed in the context of WM.

To test this question, we combined the PRP paradigm with a WM task, creating a complex WM span task. If the executive functions of WM and PRP are indeed related, then an interaction between the two tasks should be evident. Participants were presented with a sequence of letters to remember, followed by a processing block in which they had to perform either a single task or a dual-task, and finally were asked to recall the letters. Results (Chapter 2) showed that recall performance decreased when performing a dual-task as compared to performing a single task. This supports the assumption that PRP dual-tasks demand executive functions of WM. Following this, two other experiments were performed each with a different parametric modulation of the processing demands of the PRP dual task; response order (fixed vs random; Chapter 3) and stimulus onset asynchrony (SOA, short vs long; Chapter 4) of the component tasks. Recall performance was lower after a more difficult dual-task compared to an easier dual-task, which again indicates that demands on executive functions are increased in the dual-task.

While previous neuroscientific research indeed showed that dual-tasks as well as WM tasks rely on lateral-prefrontal cortices (LPFC), it remains unknown whether both tasks activate the same areas or different sub-areas of the LPFC. Therefore, this study (Chapter 6) investigated how the neuroanatomical correlates of both dual-task and WM compare to each other. The brain activation for the PRP and WM tasks showed considerable overlap as well as some differentiation. Both tasks activated, among other areas, the inferior frontal junction. With respect to differences, the PRP task activated more the inferior middle frontal gyrus (MFG) whilst the WM component activated more the superior MFG. Thus, results support the assumption that PRP dual-tasks demand the executive functions of WM. This will allow us

to inform theoretical models of cognition and to get a better understanding of human cognition. Future studies can build on this in order to create a more consolidated conceptualisation of the relationship between WM and multitasking.

Keywords: PRP, dual-task, working memory, executive functions, behavioural experiments, fMRI

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Chapter 1 : Introduction

1.1 Introduction to multitasking

An important aspect of everyday life is our capability of performing two tasks at the same time, so-called dual-task or multitasking performance (Pashler, 1993). In work and home environments, we can easily think of examples of performing task simultaneously like cooking breakfast while watching the news on television. In the workplace a person might be answering emails and making phone calls simultaneously in the hope of performing more work in a given time period. Generally speaking, the term multitasking refers to the concurrent performance of at least two tasks and in this thesis these multitasking situations will be studied. These situations are an essential aspect of interacting with our surrounding environment. However, people are usually not aware of having difficulties performing dual-tasks unless the tasks are very demanding (Pashler, 1994). For the remainder of this thesis, the terms dual-task and multitasking will be used interchangeably and will refer to performing two tasks at the same time.

It has been shown for a number of circumstances that people are not able to perform certain mental operations in parallel, resulting in performance decrements shown by slowed response times and/or increased error rates in dual-task, as compared to the single-task, conditions (Pashler, 1994). There is strong evidence that this cost results from a central attentional bottleneck in dual-task performance which limits certain mental operations to serial processing (Marois & Ivanoff, 2005; Pashler, 1994; Tombu et al., 2011). The aim of the present thesis is to investigate executive functions. In more detail, it investigates whether the existence of such a central attentional bottleneck in dual-task processing results in demands on the executive functions of working memory (WM). These executive functions may for instance resolve interference and coordinate task processing at the stage of the bottleneck.

1.1.1 Processing stages

When discussing multitasking, it is helpful to look at a model showing the processing stages of information and task performance to understand task processing. Cognitive task processing for task performance can be described in three stages (Logan & Gordon, 2001; Pashler, 1994; Ruthruff, Miller, & Lachmann, 1995), which can be illustrated using the task of determining the colour of a circle presented on the screen. First is the perception stage, which involves the observation and analysis of the external stimuli. In this case, the participant sees the circle on the screen. This is followed by the response selection stage which deals with the decision making process where an action is required for each stimulus, e.g. which button press belongs to which stimulus. For the current example, this means deciding whether to press the “Y” key for answering yellow to the colour of the circle or “B” for answering blue. The final stage is the motor execution stage which is the actual moving of the finger to respond to the stimulus by pressing the corresponding key defined in the response selection stage.

1.1.2 Introduction to Psychological Refractory Period (PRP) paradigm

One of the most widespread paradigms used to investigate the central attentional bottleneck which forms the basis of the present study is the Psychological Refractory Period (PRP) paradigm, in which participants have to perform two two-choice response tasks simultaneously. Two stimuli (S1 and S2) are presented rapidly after one another and are separated by a (variable) stimulus onset asynchrony (SOA) with each stimulus requiring a specific response (RE1 and RE2, with reaction times RT1 and RT2, respectively) as is shown in Figure 1.1 (De Jong, 1995).

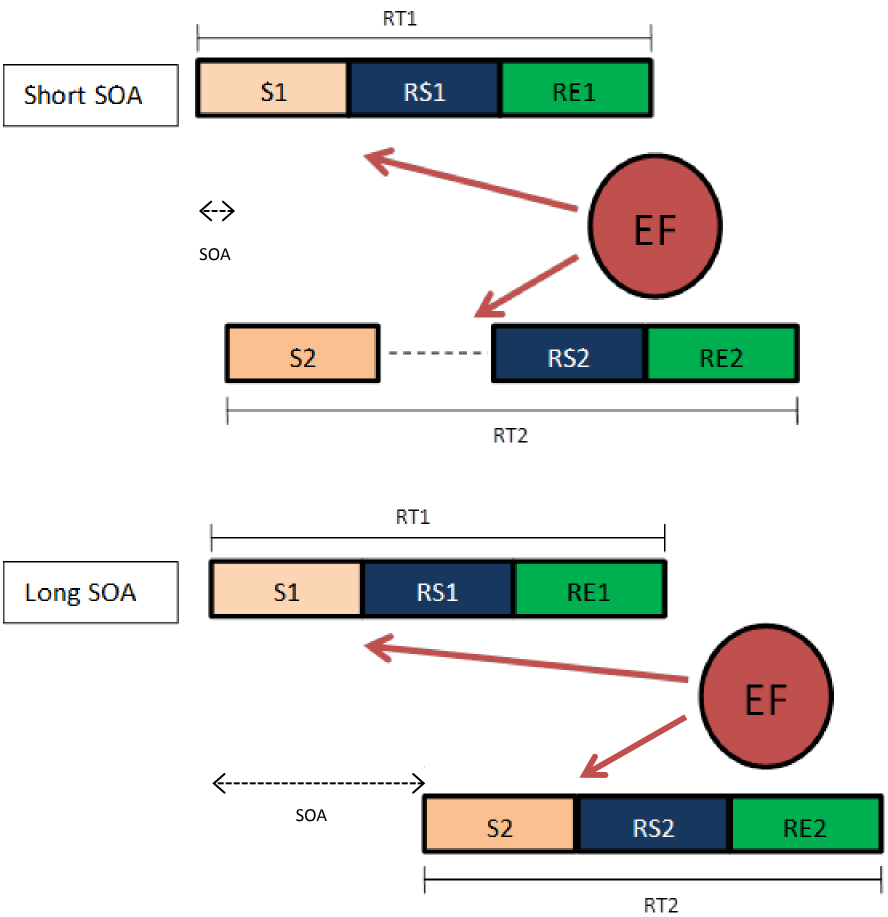


Figure 1.1: The response-selection theory of the PRP Paradigm. The first stimulus (S1) is shown before the second stimulus (S2) with a variable stimulus-onset-asynchrony (SOA) and reaction times (RTs) are measured to each stimulus. The dotted line in the short SOA condition shows the waiting time (sometimes called ‘slack’) for response selection 2 (RS2) which needs to wait until the response selection for stimulus 1 (RS1) has been finished, e.g. the bottleneck, after which the response will be executed (RE1/RE2). Executive functions (EF) might be needed to resolve this interference. Adapted from (Marois & Ivanoff, 2005).

The typical finding in this dual-task paradigm is a prolonged response time to S2 (RT2), as compared to when S2 is presented in isolation (single task). In addition, RT2 increases with decreasing temporal overlap between the tasks (i.e. shorter SOA between S1 and S2) whereas RT1 is usually largely unaffected by the SOA (De Jong, 1995; Lee & Chabris, 2013; Logan & Gordon, 2001; Marois, Larson, Chun, & Shima, 2006; Meyer & Kieras, 1997; Pashler, 1994; Schubert & Szameitat, 2003; Smith, 1967). This prolongation of RT2 with shorter SOA is a phenomenon often referred to as the PRP-effect and reflects the central limitation in people's ability to successively perform more than one task at a time. If the SOA is short, both tasks compete for resources in a processing bottleneck, and the second task has to wait until processing of the first task has finished (Logan & Gordon, 2001; Marois & Ivanoff, 2005; Ruthruff et al., 1995; Schubert & Szameitat, 2003). It is a highly robust effect which has been observed in a wide variety of tasks including simple RT and choice RT tasks, a range of combinations of response modalities (such as vocal-manual, foot-manual, or manual-manual) and a variety of combinations of sensory modalities (visual-visual or visual-auditory) (Hazeltine & Wifall, 2011; Pashler, 1990; Schumacher et al., 2001; Szameitat, Schubert, Müller, & von Cramon, 2002; Tombu & Jolicœur, 2004). The current study will use the PRP paradigm in combination with a WM task which is explained in detail later.

Behavioural costs, i.e. prolonged RTs and increased error rates, are expected when executing two tasks which require the same resources to achieve good performance (De Jong, 1995; Logan & Gordon, 2001; Luria & Meiran, 2003; Stelzel, Kraft, Brandt, & Schubert, 2008; Szameitat, Lepsien, Von Cramon, Sterr, & Schubert, 2005). It is suggested that these costs are caused by a bottleneck, i.e. a limitation in the processing of temporally overlapping information, when two tasks are present (Pashler, 1994; Stelzel, Brandt, & Schubert, 2009). More specifically, it has been proposed that the *response selection stage* constitutes the bottleneck. For instance, the presentation of a circle is preceded by a tone and the participant has to decide whether the tone has a high or low pitch by pressing the corresponding key on the keyboard. The behavioural costs are in particular present in task 2, but not in task 1. The serial processing of these tasks indicates that multiple tasks have to pass the bottleneck one at a time (Moore & Weissman, 2014; Sigman & Dehaene, 2005).

Observation of the PRP effect can be taken as an indicator for the presence of a bottleneck, which is a central attentional limitation of the human cognitive system. Cognitive models of choice response tasks often assume the presence of the three processing stages of perception, response selection and motor execution (Pashler, 1994). Previous research has also shown that whilst the perception and motor response can work in parallel the response selection can only work serially (Pashler, 1993). As a consequence, response selection for stimulus 2 (RS2) has to wait until response selection for stimulus 1 (RS1) is finished, which causes the bottleneck in task processing (Dux, Ivanoff, Asplund, & Marois, 2006; Marois & Ivanoff, 2005; Pashler, 1994; Sigman & Dehaene, 2005; Spence, 2008; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2005). However, for the purposes of this thesis, only the presence of a bottleneck is of relevance, and not at which processing stage(s) it is located.

The presence of this bottleneck might require further executive functions to coordinate the tasks at the bottleneck. Some people have argued that you need executive functions to control dual-task performance (Baddeley, 1996a; Brown, Collier, & Night, 2013; De Jong, 1995; Kieras & Meyer, 1997; Logan & Gordon, 2001; Meyer & Kieras, 1997; Szameitat, Schubert, Müller, & Von Cramon, 2002; Szmalec, Kemps, & Vandierendonck, 2005). Other researchers have argued against this view and said that there is no need for executive functions to coordinate dual-task performance (Adcock, Constable, Gore, & Goldman-Rakic, 2000; Bunge, Klingberg, Jacobsen, & Gabrieli, 2000). Thus, the role of executive functions in dual-task performance is really unknown and is an open and unresolved question. Accordingly, the aim of this study is to understand the role of executive functions in multitasking. This is relevant for both everyday life situations such as driving and using the phone and for certain workplace situations like air traffic controllers and modern day office workers who also have to work in workplaces that demand high multitasking.

1.1.3 Why might this bottleneck result in the need for executive functions?

Previous evidence and theoretical models suggest that the presence of a bottleneck might demand further processes to coordinate the tasks at the stage of the bottleneck. Results of an experiment on dual-task interference support a multi-component account of executive functioning (Cooper, Wutke, & Davelaar, 2012). This means that different aspects of dual-tasks draw differently upon processing supporting executive functions. The executive demands in a dual-task can be increased by either increasing the task coordination (e.g. using a random task condition) (De Jong, 1995; Luria & Meiran, 2003; Szameitat, Schubert, Müller, & Von Cramon, 2002) or by changing task set maintenance (e.g. manipulating the stimulus-response mappings) (Stelzel et al., 2008) which are both described below.

De Jong (1995) investigated the role of preparation in overlapping task performance. A two-choice response task had to be performed in a dual-task condition with auditory and visual stimuli. By varying the task order and the instructions regarding this task order, it was shown that the order of task performance is explicitly planned and prepared in advance; a longer RT1 was found when participants were instructed to respond to the stimuli in order of presentation compared to responding in the same order as the previous trial. These first experiments focused on the preparation of the task that participants were expected to perform first and showed that subjects were unable to maintain proper preparation for two independent tasks at the same time. Hence, the order of task performance in the

PRP paradigm is prepared in advance. This also shows that the sequential performance of overlapping tasks is controlled by initially allocating the bottleneck to the first task.

In a further experiment De Jong (1995) manipulated the order of the tasks; the tasks were either presented in a fixed or an alternating order, giving a perfect prediction of the task order of the upcoming trial. Results showed the classic PRP effect and also more errors were made in the alternating task order. The response times to the first stimulus were only slightly slower in the alternating order conditions than those in the fixed order condition which shows that subjects were able to prepare for the first task in the alternating order condition but the second response times were much slower in the alternating order condition. The main finding is that participants automatically prepare to process tasks in the same order again (e.g. auditory-visual, then again auditory-visual). These results suggest that subjects not only prepare for the first task but also for the subsequent switch to the second task. In the alternating order condition, subjects were able to complete the first part of the preparation process but not so much for the second stimulus resulting in a less efficient switch to the second task and thus a slower response to the second stimulus compared to the fixed condition. This suggests that sequential preparation for and performance of a dual-task is coordinated and controlled by a multi-level control structure. This system prepares the processing system not only for the immediate response to the first task but also for a rapid response to the second task. This sequential processing might be due to the fact that the bottleneck can be allocated to and prepare for only one task at the time. Performance of multiple tasks is prepared in advance and involves a coordinate control structure, i.e. executive functions that allocate the bottleneck to the tasks in the specific order. Participants have a larger reaction time to the first task when the order changes (e.g. auditory-visual, then visual-auditory) and increased error rates. Also, responses to the second stimulus in the alternating condition (visual-auditory) are slower compared to when the second trial would have been auditory-visual again, e.g. participants are slower when the trial switches compared to repetition. To summarize, De Jong (1995) showed that participants can prepare for a) the first task and b) the switch to the second task, but not the second task itself. A switch in response order can lead to slower response times and higher error rates.

A similar study as De Jong (1995) was done by Luria & Meiran (2003) on the role of control demands in dual-task processing. A PRP paradigm with colour patch and letters was used together with three conditions defined by switching. First, in the fixed order block condition (each block consisted of 85 trials) participants performed the task in the same order in succession. Second, random blocks involved both orders presented in random succession and included two types of conditions: switch trials which are trials in which the order had just been changed and non-switch trials which are trials in which the order repeated itself. Results showed that the order alternation was associated with performance costs. Hence, Luria & Meiran (2003) confirmed De Jong's (1995) results and also showed that some control processes operate at central stages in the task processing and not only on the coordination of the motor responses.

Stelzel et al. (2008) investigated the effect of task coordination and task set maintenance. In the dual-task, participants had to respond to both tones and digits whilst the response set size was manipulated across blocks by varying the number of relevant stimulus-response mappings. In the first (set-4) condition two of the four sensory stimuli were mapped onto the same motor responses while in the second (set-8) condition the sensory stimuli were mapped onto four different motor responses. Thus, the amount of relevant motor responses, and hence the overall task set size, doubled across conditions. Results showed significantly slower RTs in set-8 compared to set-4 conditions attributed to the increased set-size and associated higher demand on executive functions (Stelzel et al., 2008).

Sigman & Dehaene (2005) further investigated the bottleneck during the processing of a dual-task. In their study one task was a tone-discrimination task that involved differentiating between a high or low pitch. The other task was a visually presented number comparison in which participants decided whether the digit on the screen was smaller, or larger, than 45. This number task was manipulated using three different factors: notation (whether the number was presented in Arabic digits or in spelled words), distance (the numerical distance between the presented number and 45) and response complexity (whether participants were asked to tap once or twice as a response). Here, the tone is a probe to study the effects of manipulations on different stages of processing of the number task. Results showed that when the task demand was increased in perceptual or central stages, participants took longer to respond whereas when the demand was increased in the motor stages, RTs in the first task were longer. According to the authors, this indicates the presence of the bottleneck and the involvement of executive functions. Moreover, these executive functions seem to be involved at the start of response selection, just after the perception stage of the first task has finished.

Taken together, there is empirical evidence showing that the presence of a central attentional bottleneck in PRP dual-tasks requires additional control processes. Switching and inhibition are important executive functions needed in the performance of random dual-tasks (De Jong, 1995; Luria & Meiran, 2003) and updating seem to be an important executive function when it comes to task set maintenance (Stelzel et al., 2008). Therefore, both task order and task set manipulations in dual-tasks affect the demands on executive functions. Executive functions are involved in dual-tasks and resolve interference (Sigman & Dehaene, 2005).

In addition to this empirical evidence, two theoretical models have been proposed which necessitate additional control processes in PRP dual-tasks. First, Meyer & Kieras (1997) developed a production-system model to study human performance called Executive-Process Interactive Control

(EPIC). This model contains two stages: first how several individual tasks are performed and second how individual tasks are coordinated during multitask performance. The model consists of several memory stores and processing units which interact with each other in a non-hierarchical way. The processing units contain visual, auditory and tactile modules that receive inputs from the task environment. There is one other processor, the cognitive processor, which combines the outputs from the processing units and the memory stores to select the appropriate responses. In other words, the cognitive processor sets specific rules for performing a task in relation to the contents of the memory stores and the stimuli inputs received from the external/task environment. The EPIC model leads to several conclusions: at a cognitive level, sets of rules can be applied simultaneously for executing the procedures of multitasking. However, people's capacity to process information is limited and to cope with these limitations scheduling strategies are used. These strategies are mediated by distinct executive processes that coordinate the several tasks. EPIC is used to model human performance and in principle EPIC, as humans, is able to do two tasks in parallel. However, it is a strategic decision not to do so and this is incorporated in the model by having two distinct modes: the immediate and deferred mode. The immediate mode performs a task with the highest priority for response output. In the PRP paradigm, this will be task 1 at short SOAs and task 2 at long SOA after task 1 has been completed (Kieras & Meyer, 1997; Meyer & Kieras, 1997b). When the SOA is short, stimulus identification and response selection for task 2 may proceed at the same time as task 1 is being performed, but task 1 is prioritized. Selected task 2 responses are stored temporarily in working memory (deferred mode). Response deferment is coordinated by an executive process that controls when the response for task 2 is executed following task 1. In other words, task 1 is put into an "immediate" mode and task 2 into a "deferred" mode. When the SOA is long, stimulus identification and response selection for task 1 is usually finished before stimulus identification of task 2 starts.

A second theoretical model of control processes in PRP dual-tasks called executive control of visual attention (ECTVA) was proposed by Logan & Gordon (2001). This model relies upon two processes; first visual attention deals with the selection between tasks in dual-task situations. Second, an executive control system that controls this subordinate process of visual attention. In this model, there is an early perceptual stage that encodes stimuli from the environment and a later motor stage which produces an overt action based on the representation of the stimuli processed by the ECTVA. Representation of tasks is hierarchical, with the lower level specifying each task separately and the higher level identifying the order in which the tasks occur. This task order depends on the order of the stimuli using a serial process and a first come, first served rule. Both tasks can be performed in parallel but parallel performance takes longer than successive serial performance, because of the time needed to resolve crosstalk between the tasks. Empirical results showing crosstalk effects on RT1 indicate task 2 response selection began before task 1 response selection finished. Furthermore, crosstalk between the tasks depended on the task set being the same for task 1 and task 2. No crosstalk was found when the task set changed from task 1 to task 2. To summarize, the executive functions of this model transmit the stimuli from perception and memory to motor actions as well as resetting the evidence accumulation process after a response has been made to enable the next response.

The proposed control processes involved in executive functions in the dual-task processing were subdivided into sequencing, switching, inhibition, activating, and monitoring (Baddeley, 2012b). Switching, or shifting, refers to changing from one task to the other and transferring attention between tasks (Baddeley, 1996a). Inhibition refers to keeping the focus of attention on the stimuli or task and avoiding other distractors to take that attention away (Friedman & Miyake, 2004; Miyake et al., 2000). Sequencing means scheduling and executing the tasks in the correct order (Shallice, Burgess, & Robertson, 1996), which is also related to the monitoring/updating stage that regulates the performance of both tasks. These functions of the executive system were studied by Miyake et al. (2000). Several standard WM tasks were used including the Wisconsin Card Sorting Test (WCST), the Tower of Hanoi (TOH), Random Number Generation (RNG) and the operation span task. Results of structural equation modelling showed that the three target executive functions (shifting, inhibition and updating) contribute differentially to the performance in the complex executive tasks used in this study. More specifically, shifting seems to play a role in WCST performance and dual-task coordination (Miyake et al., 2000; Monsell, 2003). Inhibition seems to contribute to TOH and WCST performance. Both inhibition and updating are related to random number generation performance which also involves short-term memory (STM) (Miyake et al., 2000). Therefore the main functions of the central executive functions described by Miyake et al. (2000) match those needed to perform well in PRP dual-tasks (Baddeley, 1996a, 2012b; Szameitat, Schubert, Müller, & Von Cramon, 2002).

These findings are in accordance with an active scheduling account of how the two tasks are processed if a capacity limited processing bottleneck is present. This is in contrast with a passive queuing account, where the tasks are processed on a first-come, first-served basis. Here, when the bottleneck is occupied by processing the first task, the second task is held in a passive queue until the first task has been finished and this account does not predict increased cognitive demands relating to the scheduling, monitoring and controlling task performance (Jiang, Saxe, & Kanwisher, 2004; Lehle, Steinhauser, & Hübner, 2009). Jiang et al., (2004) assessed this in a functional magnetic resonance imaging (fMRI) study which manipulated the dual task SOA. They argued that demands on active scheduling should be present only at a short SOA (100 ms), but not at a long SOA (1500 ms). Active scheduling should result in additional activation in brain areas related to such scheduling demands, as for instance the lateral prefrontal cortices. However, Jiang et al., (2004) were not able to find such areas, inferring that short and long SOAs impose the same mental demands on control processes and thus concluding that the passive queuing account is the more likely model for PRP tasks, but see e.g. (Szameitat, Schubert, Müller, & Von Cramon (2002)). A further study showing more support for passive queuing rather than active scheduling was reported by Lehle et al. (2009). In this behavioural study they manipulated participants to use either a serial or a parallel processing strategy while judging identical dual-task sets. The task was the judgement of parity of the stimuli. Stimulus one and two were congruent on half of the trials, i.e. had the same parity, and were incongruent on the other half, i.e. had the opposite parity. In addition to overt performance (reaction times and error rates) measures were taken of both mental effort (via questionnaire) and electrodermal activity. Results showed increased parallel processing performance costs relative to those for serial processing (longer reaction times and higher error rates) even though serial processing was judged as more effortful. There was no significant effect of the instruction condition on the skin conductance responses (SCR) but there was a significant main effect of congruency on the SCR frequency, increased SCRs occurred on the incongruent trials than on congruent trials. Hence, the electrodermal activity appeared to be less influenced by processing strategy. They concluded that the preference for a parallel strategy in dual-tasks seems to reflect a compromise between optimizing task performance and minimizing mental effort and they supported the passive queuing approach, e.g. no additional executive function resources were needed to perform the tasks well.

Additional evidence for the role of executive functions in a PRP paradigm was found in an fMRI study (Szameitat, Schubert, Müller, & Von Cramon, 2002). The paradigm consisted of two 3-choice response tasks, an auditory and a visual one, with both fixed and random presentation order of the component tasks in the dual-task conditions. The classical PRP effect was shown, i.e. prolonged reaction times and increased error rates in the dual-task conditions. Results showed that there was additional dual-task specific activation compared with the single task conditions. One interpretation is that this additional activation might reflect the demands on executive functions of coordinating the interfering processes of the component tasks in the dual-task. This interference between tasks is due to the bottleneck which can only process one task at a time. On the other hand, dual-task specific activation might be due to other increased processing occurring only in the dual-task and not in the single task conditions, e.g. keeping two stimulus-response mappings in mind. To summarize, neuroimaging results are in agreement with the idea that executive functions schedule the processing order of the tasks, reinstate task processing of the interrupted tasks when the bottleneck has finished processing of the other task and switch between processing the different streams of task information. A larger review on neuroimaging results relating to dual-task performance is given in Chapter 5.

To conclude, the PRP effect, i.e. slowing of RT2 with decreasing SOA, has been observed in a wide variety of tasks involving several response and stimulus modalities. These behavioural costs are only present in the second task and have been explained by a capacity limitation of the human cognitive system, i.e. a bottleneck. This has generally been attributed to a need for the response selection for the second task to wait until the response selection for the first task has finished. Several studies indicated a need for executive functions in order to supervise and coordinate the tasks at the bottleneck. De Jong (1995) found that participants automatically prepare to process tasks in the same order again and that whilst participants can prepare for a switch to the second task they cannot prepare for the second task itself. A similar study was performed by Luria & Meiran (2003) who showed that the alternating task order was associated with performance costs. Therefore, it is suggested that subtask sequence involves more central cognitive processes not simply the coordination of the motor responses. This behavioural research suggests the involvement of executive functions in terms of preparation and order control in a dual-task situation.

Two models were discussed that explain the role of executive functions in a PRP paradigm. First, the EPIC model by Meyer & Kieras (1997) is used to model human performance and contains two distinct modes. In the PRP paradigm, the first task is put into an "immediate" mode and the second task into a "deferred" mode. The cognitive processor in this model combines the output from the processing units and the memory stores to select the appropriate responses and this suggests that additional executive functions are required in the PRP paradigm. Second, the ECTVA model of Logan & Gordon (2001) focuses on executive functions transmitting the stimuli from perception and memory to motor actions. Furthermore, executive functions reset the evidence accumulation process after a response has been made to enable the next response. Importantly, both of these theoretical models are based upon the involvement of executive functions for task coordination. Taken together, several empirical studies as well as theoretical models suggest that the presence of a bottleneck in a PRP dual-task requires additional control processes.

In more detail, the proposed control processes were described as sequencing, switching, inhibition and updating. However, this active scheduling account of a bottleneck processing has been challenged (Jiang et al., 2004; Lehle et al., 2009), so that the first aim of the present study is to provide further evidence for an active scheduling account by using a new methodological approach which is described in detail below. Taken together, the role of executive functions in multitasking remains an open question, although research has indicated its potential need, but so far this role remains unresolved.

1.2 Executive functions in more detail

Since the aim of this study is to understand the role of executive functions in multitasking, it seems appropriate to discuss the general nature of executive functions in more detail. Executive functions are of central interest to cognitive psychology. These functions can be described as the mental processes for the regulation and control of other cognitive processes, in particular for complex tasks.

1.2.1 The Supervisory Attentional Model (SAS)

A popular model of executive functions is the Supervisory Attentional System (SAS) of Norman & Shallice (1980). The most basic elements of action control in this model are schemas, which are learned sequences of thoughts and actions. These schemas are like scripts and specify behaviour in known situations under the influence of environmental conditions. Schemas can be activated directly by perceptual stimuli from the environment or by the output of schema for recently activated stimuli (internally). There is a huge but finite quantity of schemas and these are organized hierarchically. Low level schemas represent simple actions whereas high level schemas specify more complex actions. In the model of Norman and Shallice there are two main processes involved in the control of the schemas. The first process is contention scheduling which is a low level mechanism involved in the initiation of the appropriate schema under routine/automatic situations that can also prevent simultaneous execution of several schemas. The second component is the SAS which controls the schema activation for unique, or non-routine, procedures. This is a higher-level mechanism and can exert control over contention scheduling. It is needed for novel situations, complex actions, planning and problem solving. It monitors schema execution and if there is no existing schema that can resolve the problem, a new schema can be created and implemented. An overview of the model of Norman and Shallice is depicted in Figure 1.2. Thus, the SAS is a system which controls action scheduling, i.e. contention scheduling, by influencing schema activation probabilities when applied to novel problems or during routine situations (Norman & Shallice, 1980). Multitasking is an excellent example of SAS involvement, because the system needs to activate different schemas due to the different stimuli from the environment. This is followed by contention scheduling to determine which response to select and execute first. Therefore, the SAS is involved in the higher level control of action and coordinates sub-processes. To summarize, the SAS is involved in the executive component of task coordination; to store, control and process relevant information in order to activate the correct schema to make an appropriate action to the environment.

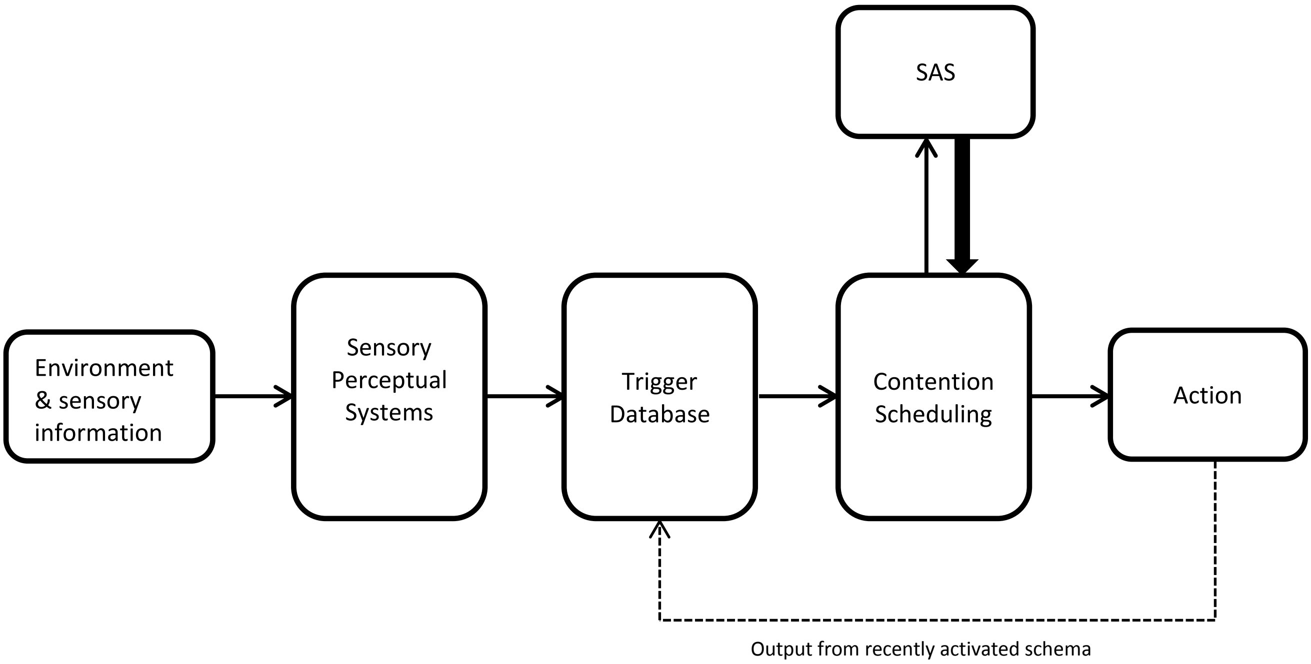


Figure 1.2: The SAS model, adapted from Norman & Shallice (1980).

1.2.2 Executive functions in the context of working memory

The control processes associated with bottleneck processing, i.e. switching, inhibition, activating, and monitoring, are all prototypical key functions of the so-called executive functions of working memory (WM) (Baddeley, 1998; Baddeley, 1996a, 2012b; Baddeley, Sala, & Robbins, 1996; Miyake et al., 2000). Therefore, the second aim of the thesis was to determine whether the potential executive functions needed to coordinate bottleneck processing are related to the executive functions of WM. In this section models of WM are discussed.

WM is often defined as the short-term storage of information (maintenance) plus controlled attention (Engle, 2002). In virtually all models of WM, this controlled attention can be equated to executive functions which enable the manipulation of the contents of short-term memory (e.g. the Central Executive System (Baddeley & Hitch (1974)) described below). In a slightly broader sense, the executive functions of WM have been described as mental processes for the regulation and control not only of the contents of short-term memory but also of other cognitive processes, especially complex tasks (Miyake et al., 2000). The most prototypical functions to exert this control on memory contents and other cognitive processes are inhibition, switching, and updating (Miyake et al., 2000).

In the WM literature (which is surprisingly separate from the literature on the central attentional bottleneck and the PRP paradigm) numerous models of WM have been proposed. However, many of them are very specific to memory processes and are not easily applied to demands on controlled attention arising from processing a task such as the PRP task. One of the few exceptions is the time-based resource sharing (TBRS) model proposed by Barrouillet & Camos (2007), which makes very strong and testable predictions about the interactions between memory-related and task-related processing demands. Accordingly, the current study employed the TBRS model as a conceptual framework for WM, but first two other WM models are discussed.

1.2.2.1 The working memory model of Baddeley & Hitch

According to the first model, WM can be defined as the mechanisms that keep information active and available for short-term storage while performing complex tasks (Baddeley, 1986, 1997, 2010; Miyake & Shah, 1998). WM is composed of the functions of cognition that enable humans to understand and represent their immediate surroundings and to maintain information about their immediate past experience (Baddeley & Hitch, 1974).

Baddeley & Hitch (1974) proposed a model of WM consisting of two slave systems; the visuo-spatial sketchpad and the phonological loop which are both coordinated/supervised by the central executive system. These three components (the two slave systems and the central executive) will be described in more detail here and are depicted in Figure 1.3 (Baddeley, 1996a, 1996b, 2012; Baddeley & Hitch, 1974).

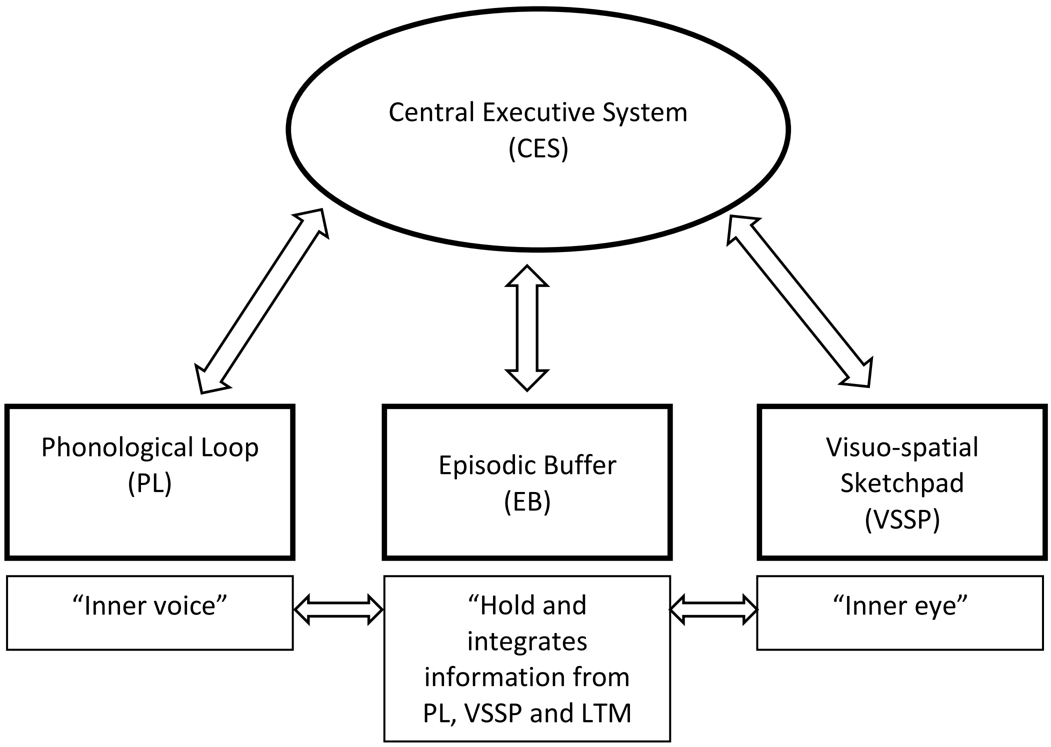


Figure 1.3: The WM model of Baddeley and Hitch.

The phonological loop (the “inner voice”) deals with acoustic and verbal information. It is the short-term memory for speech-based information and consists of two components. The first component is the phonological store which holds items passively online and is subject to rapid decay over time. The second component is the articulatory rehearsal component which prevents the decay of the memory traces in the phonological store by refreshing them item by item (Baddeley, 1986, 1996b, 1997).

The visuo-spatial sketchpad (the “inner eye”) is for visuo-spatial data and stores information about what we see such as remembering the location of objects in space and their shapes and colours. This slave system is also divided into two components; the visual cache storing information about form and colour (visuo-spatial information) and the inner scribe which deals with spatial and movement information (e.g. rotating an object) (Baddeley, 1996b, 2007, 2012).

A fourth component was later added to the model, the episodic buffer. This component can be seen as a third slave system and it combines information across the other components (Baddeley, 2000). It integrates information from the phonological loop, the visuo-spatial sketchpad and also long-term memory to create integrated units of information and a unified perception (Baddeley, 2000, 2007, 2012; Baddeley, Allen, & Hitch, 2011).

The central executive system acts as a supervisory system and coordinates and controls the information from, and to, its two slave systems, which only function as a short-term storage. If the items are not refreshed, the information decays in approximately 2 seconds (Baddeley, 1986, 1997, 2012a; Baddeley & Hitch, 1974; Baddeley, Sala, & Robbins, 1996). The central executive system is used to shift between tasks, for selective attention and for inhibition. It determines which components, either the phonological loop or visuo-spatial sketchpad, are accessed for information (Baddeley, 2003; Baddeley, 1986, 2007; Baddeley et al., 1996). It manages the interaction between these slave systems and the episodic buffer (Baddeley, 1986, 2012a; Sala, Baddeley, Papagno, & Spinnler, 1995). This is related to the SAS model explained earlier; the SAS is involved in the executive component of WM, to store, control and process relevant information. This suggests the central executive system is likely to be required in PRP tasks. The central executive system controls the input from both stimuli in the PRP tasks and coordinates the appropriate responses to both of them. It is used to switch between the tasks and to make sure that the correct responses are selected and others are inhibited (Baddeley, 2003; Baddeley, 2012b; Baddeley et al., 1996).

Evidence for this model was also found in a dual-task paradigm since performing two tasks concurrently places a demand on the central executive system. The aim of the study was to investigate if participants can use different parts of WM at the same time by asking them to perform two tasks simultaneously. The primary task was a short-term memory task consisting of a number recall. The secondary task was complex and demanding, e.g. reasoning. Results showed that storage (phonological loop and visuo-spatial sketchpad) was separate from central processing (central executive system) (Baddeley & Hitch, 1974). The two tasks can be performed with much less interference than predicted by a common short-term memory system for verbal and spatial information. In other words, performance of two tasks at the same time by using two separate perceptual domains (auditory and visual) was almost as efficient as performing the tasks individually. This indicates the existence of two distinct systems for verbal and visual information which is supervised by the central executive. This was confirmed in a series of experiments which used the random number generation task combined with a memory span task (Baddeley, 1996a). Participants had to use keypresses to randomly generated numbers within 0.5, 1 or 2 seconds whilst also recalling sequences ranging from one to eight items. Results showed interference between the verbal memory task and the visuo-spatial generation task. Furthermore, the degree of disruption of the random number generation increased with concurrent memory load indicating that the system reflects a limited-capacity WM. Further studies concluded that random generation competes for the same limited capacity that is necessary to perform well in a range of tasks that depend on the central executive system (Baddeley, 1996a).

1.2.2.2 The working memory model of Engle

The second model proposed WM as a system consisting of: a) short-term memory, which is conceptualized as storage of long-term memory traces active above a threshold, b) processes and skills for achieving and maintaining the activation of those traces and c) controlled attention (Engle, Kane, & Tuholski, 1999). The authors also call their model the "controlled attention" framework. The crucial function of their WM system is keeping information rapidly retrievable when the task/environment presents interfering information that would lead to an incorrect response (R. W. Engle, 2002).

Tasks that are used to study WM in the context of this model are termed complex span tasks. A traditional simple memory span task assesses the longest list of items that a person can repeat back, not necessarily in the correct order, after a certain number of trials have been presented. Usually, these items are words, numbers or letters. In contrast, a complex memory span adds a processing demand to the demand of remembering a list of items. In such a span, encoding the memory items (e.g. letters) alternates with processing blocks (e.g. solving mathematical equations). In each of these tasks, the participant receives items to recall and also performs another attention demanding task that is interleaved between receiving the items and item recall.

In the model, WM consists of those traces in long-term memory activated above a certain threshold but these traces lose activation due to decay over time (R. W. Engle et al., 1999). In their view, the term working memory capacity (WMC) is also an important factor. The term capacity, as also used in short-term memory, usually means the limited number of items that can be stored in memory. In this view of WM, WMC is not about the individual differences in how many items can be stored but it is about the differences in the ability to control attention to maintain information in an active state (R. W. Engle, 2002). In other words, WMC is about using attention to maintain or supress information and only deals with memory indirectly. A greater WMC means that more information can be actively maintained, which is the result of a greater ability to control attention and not of a larger memory storage (R. W. Engle, 2002; Shipstead, Harrison, & Engle, 2015).

This WMC was studied by Engle et al. (1999) by examining the extent to which short-term memory and WM are involved in task switching. In their experiments several complex span tasks (reading, operation and counting) were used as well as simple span tasks. Results showed evidence in support of a unitary WM system, meaning a unique resource shared between processing and storage of memory. In other words, the simple span tasks use short-term memory whilst the complex span tasks need to share resources between processing and storage of memory when performing the concurrent task and the use of controlled attention which requires the central executive. Therefore, WMC is required for managing maintenance during concurrent processing of the concurrent task. Controlled attention is needed to deal with these processes of item recall and providing correct responses in the concurrent task. The term controlled attention of Engle et al. (1999) reflects the same processes that Baddeley & Hitch (1974) call the central executive system. It is the capacity for controlled, sustained attention in the face of interference and/or distraction. This controlled processing is needed for the maintenance of temporary goals in the face of distractors and interference, and for inhibiting these distractors to achieve the goals. It can arise in several situations. First, it can arise when tasks goals or information has to actively be maintained in WM. Secondly, it can occur when response preparation for competing tasks has to be scheduled and conflict among these tasks has to be resolved. Lastly, it can emerge when there is a need for inhibiting information irrelevant to the task that has to be performed (R. W. Engle et al., 1999).

To summarize, this model supports the idea that controlled attention is the component of WM that is important for higher-order functioning. In other words, controlled attention is of one of the critical elements of measures of WMC.

1.2.2.3 Time-based resource-sharing model

Like most other WM models, the time-based resource-sharing (TBRS) model proposes that WM consists of short-term storage (maintenance) and controlled attention (manipulation, executive functions) (Barrouillet & Camos, 2007). However, it also specifies the time course and demands of the different processes in a high level of detail. This is especially important for understanding complex WM span tasks, in which a short-term memory task is combined with an independent processing task (e.g. the operation span task that involves remembering a set of letters whilst solving math equations (Unsworth, Heitz, Schrock, & Engle, 2005)). In the current study, a new complex WM task was created by combining a short-term memory task with a PRP dual-task.

The TBRS model is based on four proposals (Barrouillet & Camos, 2007). First, it is assumed that both maintenance and processing of information require the same processing resource which they term controlled attention (Barrouillet & Camos, 2010; Engle et al., 1999). Specifically, in this proposal controlled attention is required for inhibition of irrelevant information, selection of relevant information, activation of goals, retrieval of information from memory, selection of appropriate responses and monitoring of information. Thus, controlled attention basically reflects executive functions as typically defined (Baddeley, 1996a; Engle, 2002; Miyake et al., 2000).

Second, the activation of memory traces suffers from a time-related decay when attention is switched away. Attention is needed to refresh the memory traces and to keep information in memory active and up-to date. As a consequence, when attention is switched away to another task WM recall will decrease (since it can only focus on one task at a time) (Barrouillet & Camos, 2010). Variations of this model have been proposed which suggest that memory traces do not decay, but instead deteriorate due to interference (Oberauer & Lewandowsky, 2013). However, this distinction has no implications for the current study.

Third, related to the second point, if controlled attention is disrupted or distracted while engaged in the updating required for memory maintenance, memory recall declines. Such disruptions occur in complex WM span tasks, when an additional processing task requires controlled attention besides the one required for memory maintenance. As explained below, this assumption is crucial to the current study.

Fourth, controlled attention is not divided between tasks, but instead it is devoted to one task in an all-or-nothing fashion. Sharing of controlled attention in complex span tasks is time-based which means that it is rapidly and frequently switched between maintenance and processing. According to the TBRS model, if a processing task demands more attentional resources it achieves this by occupying controlled attention for a longer period of time. When there are short time intervals in which the processing task does not require attention, then this time can be used to refresh the memory traces[1].

Thus, the TBRS theory predicts that the amount of lost information depends on the temporal density of attentional demands of the task that has to be processed concurrently with the WM maintenance. In other words, the cognitive load of a task corresponds to the time for which it uses attention and thus the length of the disruption to refreshing of memory (Barrouillet & Camos, 2010). This cognitive load depends on two variables, the rate at which the processing task can execute individual steps and the duration of each step. For example, if the processing tasks consist of solving equations, then solving a difficult equation (consisting of several steps) places a higher cognitive load on the working memory system than solving a simple equation (consisting of only a few steps). Therefore, one can say that a step is each single part of the total task that has to be processed. This is based on

[1]The TBRS model predicts information loss by decay. Souza & Oberauer (2015) agree with the TBRS model but predict information loss by loss of temporal distinctiveness which means that the relative spacing of events in time determines the degree of interference.

two assumptions. First, the processing task is always performed at the same pace, because if a task takes less time (e.g. simple instead of complex equations) participants might otherwise just solve more equations in the same time. In that case, a difference in cognitive load would show in the performance of the processing task, but not necessarily in the memory performance. In our experiments, the retention interval during which the processing tasks have to be performed was kept to the same duration. Second, participants are instructed to prioritize the processing task since otherwise one could keep memory performance at the same level even in difficult processing tasks by becoming poorer in the processing task. This assumption is also taken into account in the design of the experiments.

There are two main limits related to time. Time is not only about the total time spent on the processing tasks but also on how time is used during the task (Barrouillet & Camos, 2007). First, activation of items outside the attention focus causes a time delay and secondly executive processes are constrained by a central bottleneck which means these processes are serial and execution of the tasks depends on the actual processing time. In this way the TBRS model can be linked with the WM of Baddeley. The TBRS model is in line with the episodic buffer that holds information and representations from the distinct slave systems and combines this information (Baddeley, 2000). The central executive controls the refreshing mechanism of the episodic buffer through attention where the TBRS model comes into play (Baddeley, 2000; Barrouillet & Camos, 2010).

To summarize the TBRS model assumes that the two functions of WM, maintenance manipulation, both demand controlled attention, which is a unitary resource similar to traditional conceptualizations of executive functions. Therefore, the TBRS model predicts that memory maintenance is subject to interference from concurrent task processing (Barrouillet & Camos, 2010). Any mental process requiring controlled attention/executive functions will impair the rehearsal of information in memory. Consequently, the more difficult such a concurrent processing task is, which can be operationalized as the time it occupies the limited resource of controlled attention, the lower the recall performance in the memory task will be.

1.2.3 Summary of the link between working memory and executive functions

As mentioned earlier, humans encounter a so-called capacity limit in processing, storing and retrieving information as well as performing multiple tasks at the same time. Several theories about the nature of this capacity limit exist. One is that there is a limited pool of resources available for processing information and performing tasks (Barrouillet & Camos, 2007). Another one is that memory traces in WM decay within a couple of seconds, unless they are refreshed through rehearsal (Engle et al., 1999). As mentioned before, the PRP paradigm, in which participants have to perform two two-choice response tasks concurrently can examine the limitation in processing temporally overlapping information. The interference between the tasks is due to a bottleneck which is limited to only processing one task at a time and competition between tasks is resolved by executive functions. These functions schedule processing order, switch between processing the different streams of information and tasks to ensure that both tasks are executed in the correct way.

An important component of executive functions is WM which is the maintenance and manipulation of information for current tasks. Three models describing the relationship between WM and executive functions were considered. Baddeley & Hitch (1974) proposed a model of WM consisting of two slave sensory memory systems which are coordinated by the central executive system. In relation to the PRP paradigm, this model suggests that the central executive controls the input from both tasks and then coordinates appropriate responses to them. In the “controlled attention” model (Engle et al., 1999) it was proposed that individual differences in working memory capacity (WMC) reflect differences in the capability for controlled processing (arguably synonymous with executive functions). The model supports the idea that controlled attention is a crucial element in measuring WMC and is important for higher-order functioning (e.g. performing the PRP paradigm).

Finally, the TBRS model proposed that the two functions of WM (maintenance and manipulation) draw upon a single central resource, attention (Barrouillet & Camos, 2007). Information is maintained by fast switching from processing to storage which causes attentional refreshing of memory traces, but when this switching is delayed a cost in memory performance is observed. Memory retrieval can be predicted to suffer from severe interference from task processing of the PRP paradigm. One aim of the current thesis will be to clarify the relationship of WM and executive functions in the PRP paradigm.

1.3 Thesis Overview

1.3.1 Research Question

The current series of studies is founded on the assumption that if the additional dual-task processes are related to the controlled attention of WM, then the performance of a PRP dual-task should interact with a complex WM span task, e.g. by affecting memory maintenance performance. If such an interaction is observed, we will interpret this as supporting evidence for the so-far unresolved question whether (a) the performance of a PRP dual-task demands additional control processes and whether (b) these control processes are related to the controlled attention (i.e. executive functions) component of WM. To investigate whether a PRP dual-task interacts with WM, a complex WM span task was employed and different variations of a PRP dual-task and its individual single-tasks as processing tasks were used during the retention interval. In more detail, the cognitive load of multitasking was investigated by combining a PRP paradigm with a short-term memory/simple span task. In this way a complex WM span task was created. In this thesis, a series of experiments on the relationship between WM and multitasking with a focus on executive functions are reported. In each experiment, participants were presented with a PRP paradigm in which they had to perform either a single task (auditory or visual) or a dual-task while remembering letters.

1.3.2 Overview of experiments

In experiment 1 (Chapter 2), recall performance was analysed from a complex WM span task in which participants had to perform either a single task or a PRP dual-task as processing tasks. Performing a single task or a dual-task disrupts memory performance. However, if dual-task performance really requires executive functions, as opposed to single task performance, then it is expected that dual-task impairs memory performance more than single task performance does. Thus, if this effect is observed, it can be concluded that PRP tasks demand executive functions more than single tasks.

In experiment 2 and 3, the nature of the dual-task was manipulated. In experiment 2 (Chapter 3) a parametric manipulation was employed and this changed the order in which participants had to respond to both stimuli randomly from trial to trial (De Jong, 1995; Luria & Meiran, 2003). Experiment 2e (Chapter 3) was very similar to experiment 2c and served the purpose to control for a potential confounding factor. A replication study (experiment 2f) was conducted to confirm the initial findings. Finally, in experiment 3 (Chapter 4), the SOA of the PRP dual-task was manipulated and it tested whether the SOA had an effect on memory recall. These first behavioural chapters aim at understanding the role of WM in dual-task performance and the need for executive functions. However, the exact neural implementation of these executive functions is still unresolved and Chapter 5 will review the neuroimaging literature on both multitasking and WM. Experiment 4b (Chapter 6) describes the first MRI study where it was investigated how the executive functions of dual-tasks and WM overlap in the brain and which brain regions are involved. This was followed by fMRI study 2, experiment 5 (Chapter 7), where the interaction effect between memory load and processing task in the brain was further investigated. In the end a conclusion from both the behavioural studies and the neuroimaging studies is drawn (Chapter 8).

1.3.3 Relevance

Multitasking and memory are concepts we all use in everyday life and are very familiar with. It is important to understand the relationship between multitasking and memory in more detail to build a more consolidated conceptualisation of these cognitive functions. It can also help to solve critical issues relating to high demand work environments and improve work planning. Knowing the relationship between multitasking and WM in a better way can help us also in the clinical domain to get a better understanding of brain diseases like stroke. Finally, understanding executive systems and control processes is important to improve technology for human interfaces and overall safety while using machinery.

Chapter 2 : The present study

2.1 Introduction

The first research question of the current study was to investigate whether a central attentional bottleneck in the PRP paradigm demands executive control (as predicted by the active scheduling account). The second research question was to test more specifically, whether this additional executive control is related to the executive functions of WM. To answer these questions, we used the predictions made by the TBRS model and created a complex WM span task, in which a short-term memory task (maintenance) and a PRP dual-task (processing) were combined (cf. Liefooghe, Barrouillet, Vandierendonck, & Camos (2008)) for a highly similar approach in the context of a task switching paradigm).

In the experiments, we presented simple (e.g. single task performance) and more complex (e.g. dual-task performance) processing tasks along with a memory task. In experiment 1 it was predicted that if the dual-task demands executive functions of WM beyond the single-tasks, due to active scheduling, then the TBRS model predicts lower memory recall in the dual-task condition. This is because the executive functions related to active scheduling in the dual-task (which are not present in the single-task) occupy controlled attention for a longer time, which leaves less time for the rehearsal of the memory items.

The experiment uses recall performance in the working memory task to infer the controlled attention demands of the different processing tasks. However, for this to be valid, it is important that participants do not trade off performance in one task (processing task) for performance in the other task (memory task). To avoid this, participants received frequent feedback on their performance in the processing task and were told to be more accurate when their accuracy dropped below 80% (this is in line with research on complex span tasks, e.g. Foster et al., 2014; Unsworth et al., 2005). As a consequence, different demands on controlled attention should affect recall performance. This is related to the way the TBRS model predicts the demands of cognitive load where participants are instructed to prioritize the processing task since otherwise one could keep memory performance at the same level even in difficult processing tasks by becoming poorer in the processing task (Barrouillet & Camos, 2007).

2.2 Experiment 1a: PRP paradigm with memory loads of 4, 6 and 8 letters

The aim of experiment 1a was to test whether PRP dual-tasks demand the executive functions of WM. For this, participants had to perform a complex WM span task in which they were presented with a series of letters to remember, and then performed a processing task during the retention interval, before finally recalling the letters in the order of presentation. The processing task was either a PRP dual-task or the individual single tasks of which the dual-task was comprised. A complex WM span task is basically a dual-task, consisting of a memory component and a processing task component.

2.2.1 Method

The tasks for all experiments were programmed in E-Prime (v2.0.10.353 or v2.0.10.248) (Tools, 1996). The behavioural experiments were performed at Brunel University London, United Kingdom. Upon arrival the participant was given an information leaflet (see Appendix 1B) with general information about the experiment and contact information in case the participant had questions or comments on the experiment. When the participant had no questions, the informed consent form (see Appendix 1C) was signed by the participant and the researcher. The participant took place in front of the computer where the different tasks were displayed and was given a demographics form (see Appendix 1D) to fill in as well as the instructions of the tasks to read (see Appendix 1E).

2.2.1.1 Participants

Twenty (7 female) participants (mean age: 23 years, SD = 2.8, range 18-31 years) took part in the study after having given written informed consent. The study was approved by Brunel University's Department of Life Sciences Ethics Committee and participants received £8 for participation. The information leaflet, consent form, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 1.

2.2.1.2 Tasks

We used a complex WM span task with preload procedure which consisted of the following phases: cue, memory encoding phase, retention interval processing phase (single visual, single auditory or dual-task), recall phase (Figure 2.1). The complete design for one memory trial is displayed in Figure 2.2.

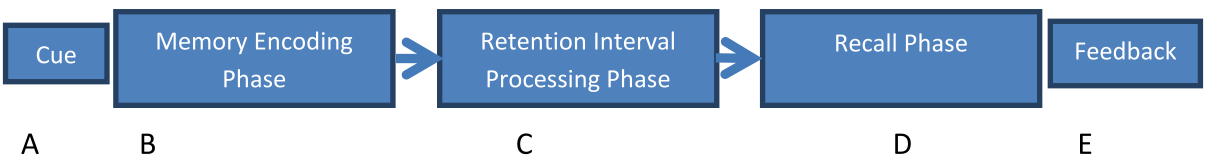


Figure 2.1: Phases of the experiment.

Cue. Before each memory trial, a written instruction was displayed in the centre of the screen for 5 seconds informing the participants about the memory load and the upcoming processing task, e.g. "6 letters – Dual Task" (Figure 2.2A).

Memory Encoding Phase. In the memory encoding phase participants were asked to memorize a series of letters presented sequentially on the screen. These letters had to be recalled in the correct order in a later stage of the memory trial. The letters 'W' and 'H' were excluded from the set because their pronunciation in English takes rather long compared to other letters of the alphabet (Crannell & Parrish, 1957). Also, the letters 'T', 'P' and 'M' were excluded since there are phonologically similar to the letters 'D', 'B' and 'N', respectively, and therefore might be difficult to rehearse (Bavelier, Newport, Hall, Supalla, & Boutla, 2006). Lastly, the vowels ('A', 'E', 'I', 'O' and 'U') and the 'Y' were excluded to make sure that the letters to be recalled could not form (pseudo-) words which would make it easier for participants to memorize the letters. Therefore the letters that were included in this experiment were: B, C, D, F, G, J, K, L, N, Q, R, S, V, X and Z. The letters in the encoding phase were drawn randomly from the set without replacement. Three different memory loads (4, 6, or 8 letters) were used. The memory encoding started with a fixation cross presented in the centre of the screen for 500 ms. Then a letter was presented for 1500 ms, followed by a 300 ms blank. Next, the subsequent letter was presented for 1500 ms, followed by a blank for 300 ms; this continued until the end of the memory load (4, 6 or 8 letters) was reached (Figure 2.2B).

Retention Interval Processing Phase. After the memory encoding phase participants had to maintain the letters in their memory recall 32 seconds later and they were not allowed to overtly rehearse the letters. During the retention interval participants performed one of the three different processing tasks, i.e. auditory single task, visual single task, or dual-task (Figure 2.2C).

Recall Phase. Finally, participants had to recall the memorized letters in the order they were presented by typing them on the keyboard. Typed letters were presented on the screen and participants could correct themselves. If a letter was not remembered, participants were instructed to press the spacebar and leave a blank space for the letter. No feedback on recall performance was given. In case the participant was a non-native English speaker, explicit instructions were given in the practice session. The participant could rehearse the letters in any preferred language. However, the participant was instructed to rehearse in one language only to avoid confusion (Figure 2.2D).

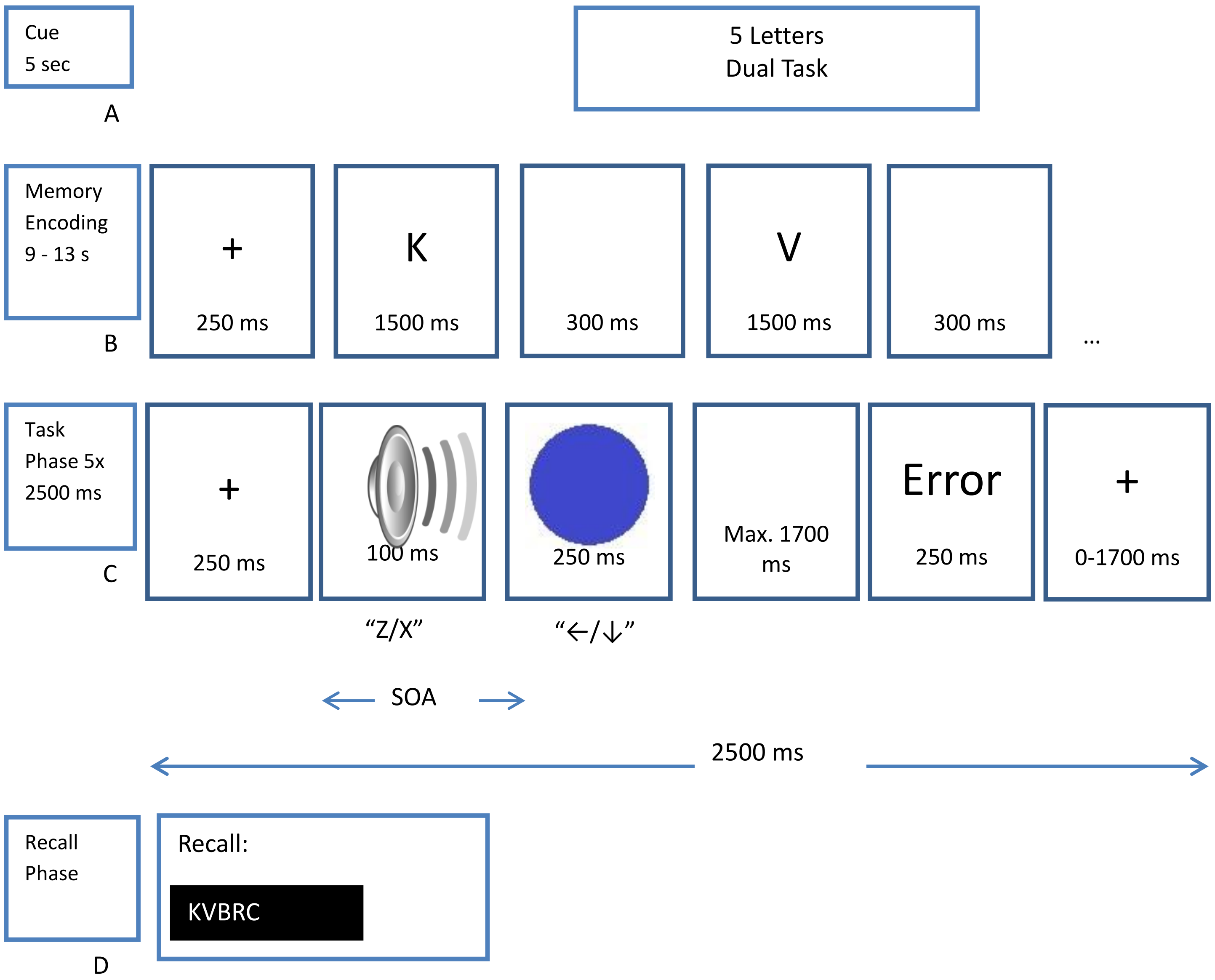

Cue
5 sec
A
5 Letters
Dual Task
Memory
Encoding
9 - 13 s
B
+
250 ms
K
1500 ms
300 ms
V
1500 ms
300 ms
...
Task
Phase 5x
2500 ms
C
+
250 ms
100 ms
250 ms
Max. 1700
ms
Error
250 ms
+
0-1700 ms
“Z/X”
“←/↓”
SOA
2500 ms
Recall
Phase
D
Recall:
KVBRC

Figure 2.2: Experimental design of the experiment. A memory trial consisted of 5 phases: A. Cue. B. Memory encoding. C. Task phase. D. Recall phase. E. Feedback.

Processing tasks.

Auditory Single Task. A trial of the auditory single task (ST-AUD) condition started with a fixation cross displayed in the centre of the screen for 500 ms. Then either a low (400 Hz) or high (1000 Hz) pitched tone was randomly selected and presented for 100 ms via speakers. When the low pitched tone was presented, participants had to press the "z" key on a standard 104-keys computer keyboard with the left middle finger and when the high pitched tone was presented they had to press the "x" key with the left index finger. From its onset, participants had 2500 ms to respond to the stimulus. Participants were instructed to respond as fast and accurately as possible. If participants made a mistake, they received an error message which was displayed for 500 ms ("Error" if an incorrect key was pressed; "Wrong Order" if responses were correct but in the wrong order (only for the dual-task); or "Too Slow" if they did not respond within 2500 ms) or if correct a fixation cross was shown for 500 ms. Finally, a fixation cross was shown for a variable duration until the end of the trial (making each trial in the processing task 4000 ms long). During the retention interval processing phase participants performed eight trials lasting 4000 ms each (Figure 2.2C).

Visual Single Task. A trial in visual single task (ST-VIS) condition was identical to the auditory single task except for the following. After the 500 ms fixation cross either a black circle or black triangle was, randomly selected and presented on the screen for 300 ms. When a black circle was shown, participants had to press the "n" key on keyboard with the right index finger and when a black triangle was presented, the "m" key with the right middle finger (Figure 2.2C).

Dual-task. In the dual-task condition (DT), both the auditory and visual stimuli were presented. Three different SOAs were used, 50 ms, 125 ms and 200 ms, which varied randomly. Participants were instructed not to group their responses (Pashler, 1994). After the 500 ms fixation cross either a high or low pitched tone was presented and after the variable SOA either a black circle or triangle was presented. Participants responded first to the auditory and then to the visual stimulus by pressing the same keys as in the respective single tasks. The other parameters were the same as described in the single task conditions. All processing tasks consisted of eight trials lasting 4000 ms each (Figure 2.2C).

Procedure.

Participants performed 36 memory trials (6 dual-task memory trials for each of the three memory loads (4, 6, 8 letters), and 6 single task (3 auditory and 3 visual) memory trials for each memory load). The order of conditions (memory load and processing task) was individually randomized for each participant. The main experiment lasted about 30 minutes. Before the main study, participants practiced all tasks for approx. 15 min. After the experiment, participants were asked to fill in a questionnaire about their opinion on the experiment, the language in which they rehearsed the letters and the rehearsal strategy. Lastly, the participant was given a debrief form with further information about the experiment. The total experiment lasted for about an hour per participant.

2.2.2 Results

For all experiments, we assessed the impact of dual-task performance on WM by analysing the recall performance (accuracy) in the memory task. The performance in the single task and dual-task was for all experiments measured by both response times and error rates. In all experiments, we excluded participants if their mean recall for any condition deviated from the respective sample mean by more than 3 standard deviations. In experiment 1a, no participant was excluded.

2.2.2.1 Recall performance

For the analyses we calculated the relative recall performance, which is the proportion of recalled letters in absolute correct order (Liefooghe et al., 2008). For instance, when presented B, C, D, F and recalling B, C, D, F the recall score was 4 out of 4 and the recall proportion was 1. However, when B, D, C, F was recalled, the recall score was 2 out of 4 and the recall proportion 0.50, because only the first and last letter matched their serial position in the presentation sequence. To test whether dual-task performance impacts WM more than single task performance, we compared the recall scores in these two conditions.

A 2x3 repeated-measures ANOVA was conducted on the average recall performance with the factors processing task (single, dual-task) and memory load (4, 6, 8 letters). Mauchly's test indicated that the assumption of sphericity had not been violated for any of the effects. The main effect of processing task was not significant, $F(1, 19) = 0.565$, $p = 0.462$. This means that recall performance did not significantly differ between the dual-task (0.81 ± 0.11) and single task conditions (0.82 ± 0.10), irrespective of memory load, which contradicts our prediction. The main effect of memory load was significant ($F(2, 38) = 80.81$, $p < 0.001$), i.e. relative recall, averaged across task condition, was poorer for higher loads. Follow-up paired t-tests comparing all loads with each other confirmed that all loads differed from each other (all $t(19) > 5.41$, $p < 0.001$). Processing task and memory load did not interact, $F(2, 38) = 0.67$, $p = 0.52$) (Table 2.1, Figure 2.3).

Table 2.1: Relative Recall Performance of experiment 1a as function processing task and memory load.

Variable	Memory Load		
Processing Task	4	6	8
Single Task	0.96 ± 0.08	0.87 ± 0.14	0.64 ± 0.17
Dual-Task	0.98 ±0.04	0.83 ± 0.17	0.62 ± 0.17

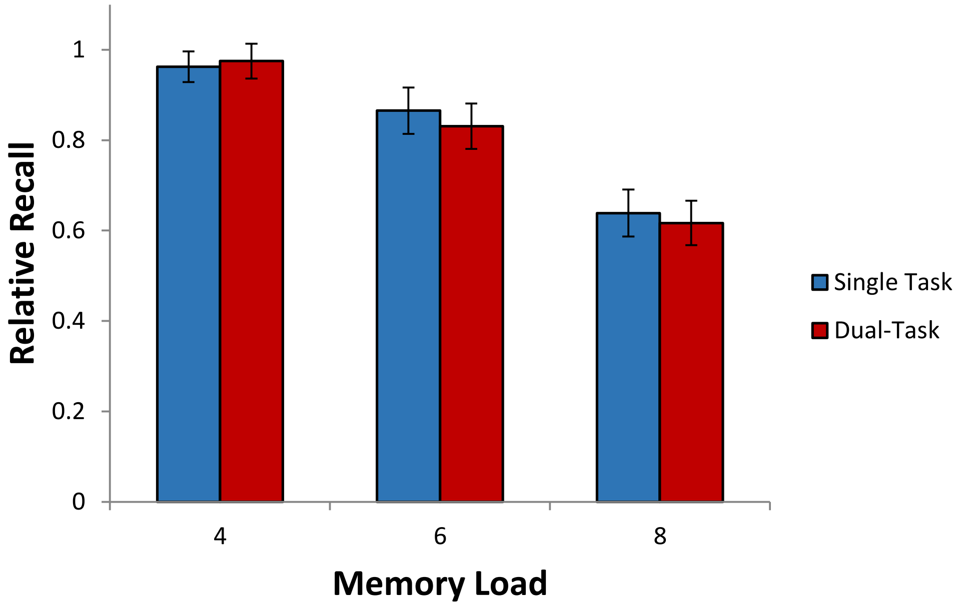


Figure 2.3: Relative recall performance for single task and dual-task conditions of experiment 1a for the three different memory loads. Error bars denote 95% confidence intervals (Loftus & Masson, 1994).

2.2.2.2 Processing Task performance

Performance in the processing tasks which were presented during the retention interval was analysed in terms of response times and error rates. In the dual-task participants always had to respond to the auditory stimulus first. This analysis focused on the existence of the PRP effect in order to show that a central attentional bottleneck was present, which may have required additional executive functions for active scheduling of the tasks.

Response times. To provide evidence that a processing bottleneck was present in the PRP dual-task, we tested for the PRP effect (i.e. an increasing RT2 with decreasing SOA while RT1 is independent of the SOA). A 2x3 repeated-measures ANOVA with the factors response (RT1, RT2) and SOA values (50, 125 and 200 ms) was conducted to analyse the PRP effect (Figure 2.4). Mauchly's test indicated that the assumption of sphericity had not been violated for any of the main effects. Analysis revealed a typical PRP effect in the DT condition. The main effect of response was significant ($F(1, 19) = 53.02$, $p < 0.001$). Due to the PRP effect, RT2 in the dual-task (1016 ± 223 ms, always visual task) were significantly longer than the RT1 in the dual-task (1131 ± 285 ms, always auditory task) for each load (all $t(19) > 3.77$, $p < 0.002$). An overview of the response times and error rates per task and memory load is given in Table 2.2 and Figure 2.6. The main effect of SOA was significant ($F(2, 38) = 38.55$, $p < 0.001$). To understand this in more detail, follow-up one way repeated-measures ANOVAs were conducted on both response times. Results showed that the RTs on the second task (RT2) significantly decreased with SOA ($F(2, 38) = 138.01$, $p < 0.001$) and the RTs on the first task (RT1) significantly increased with SOA ($F(2,38) = 30.34$, $p < 0.001$) (Figure 2.4). Mauchly's test indicated that the assumption of sphericity had been violated only for the interaction effect of RT and SOA ($\chi^2(2) = 30.16$, $p < 0.001$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.55$). Response time and SOA showed an interaction effect ($F(1.10, 20.96) = 210.60$, $p < 0.001$).

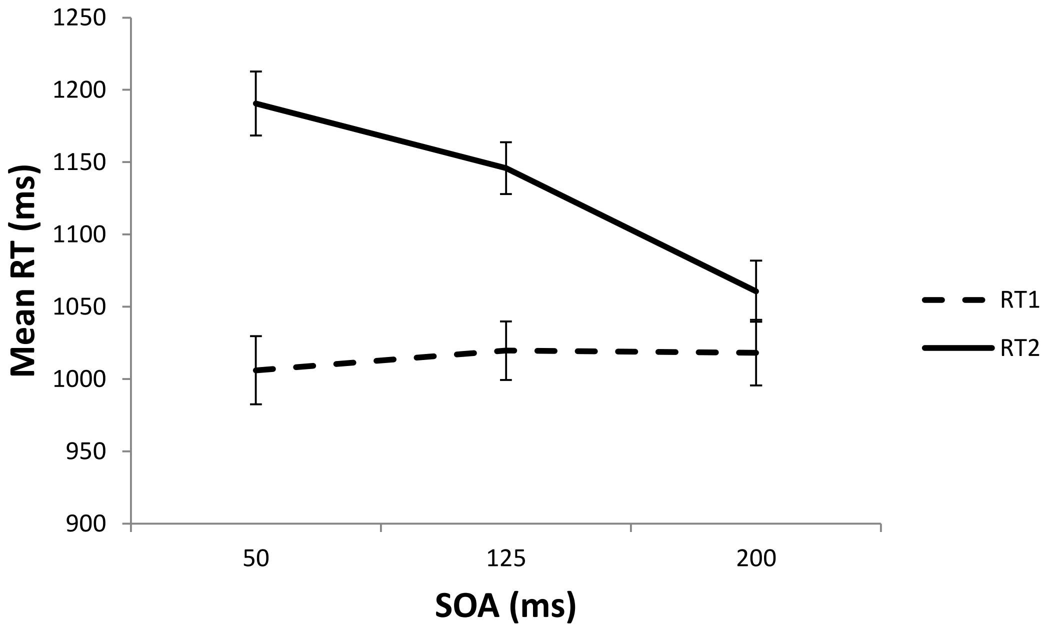


Figure 2.4: PRP effect for experiment 1a, i.e. RT2 (solid line) increases with decreasing SOA whilst RT1 (dotted line) remains roughly constant for different SOAs. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

Follow-up paired t-tests showed that RT2 significantly increased with decreasing SOA (RT2 of shortest SOA (50 ms) (1190 ± 298 ms), RT2 of longest SOA (200 ms) (1060 ± 286 ms) (all $t(19) > 2.74$, $p < 0.02$). Follow-up paired t-tests showed that RT1 of shortest SOA (702 ± 138 ms) was significantly shorter than RT1 of longest SOA (1018 ± 215 ms) ($t(19) = 14.15$, $p < 0.001$) whilst the difference between RT1 of SOA 125 ms and SOA 200 ms failed to reach significance ($t(19) = 0.09$, $p = 0.93$). The PRP effect was significant for memory load 6 and 8 by comparing RT2 of the short SOA with the long SOA (all $t(19) > 5.56$, $p < 0.001$), but just failed to reach significance in memory load 4 ($t(19) = 1.91$, $p = 0.071$). Hence, the classic PRP effect was shown for all memory load conditions by prolonged response times to the second stimulus with decreasing SOA (Figure 2.5).

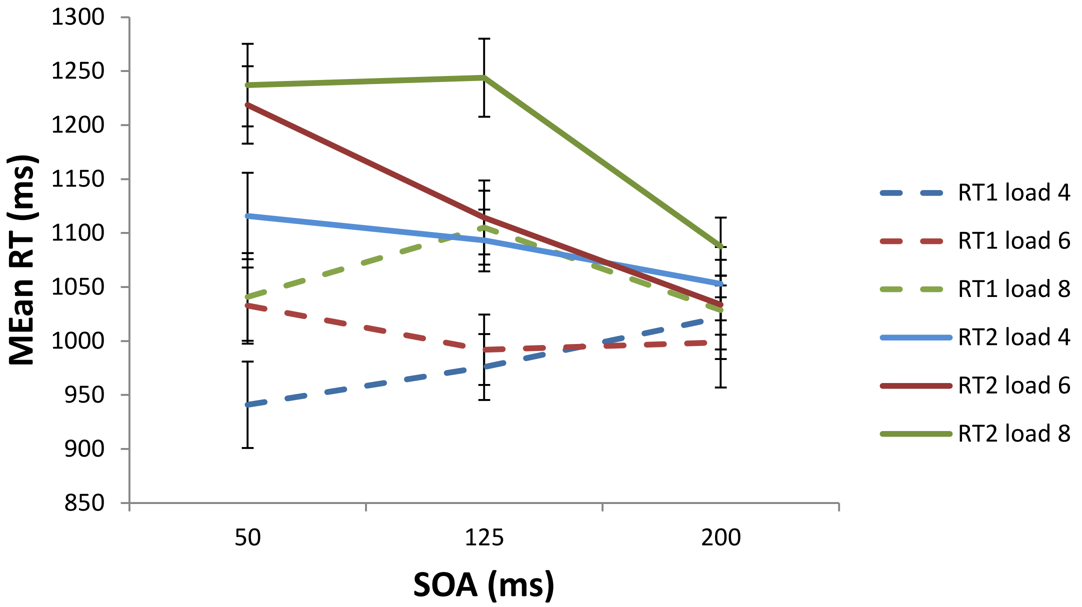


Figure 2.5: PRP effect for experiment 1a for the three different memory loads, i.e. RT2 (solid lines) increases with decreasing SOA whilst RT1 (dotted lines) remains roughly constant for different SOAs. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

Next, it was tested whether the memory load had an effect on the response times. A 2x3 repeated-measures ANOVA was conducted to study this potential effect with factors response (RT1, RT2) and memory load (4, 6, 8 letters). The main effect of response was significant ($F(1, 19) = 17.26$, $p = 0.001$). Also, the main effect of memory load was significant ($F(2, 39) = 12.98$, $p < 0.001$). Follow-up paired samples t-tests indicated that response times (both RT1 and RT2) increased significantly with memory load (all $t(19) > 2.61$, $p < 0.02$), except for the response times of the dual-task when comparing memory load 4 with 6 for both RT1 and RT2 (all $t(19) < 1.94$, $p > 0.06$). This means that response times in the higher memory load are significantly longer than the response times in the lower memory load condition. This could indicate that people were more focused on rehearsing the letters during the task condition than performing the task as fast as possible (which they were instructed to do). Thus, people might have devoted more time to rehearse the letters instead of focusing on the task performance. The next section on error rates will give more information on this. Mauchly's test indicated that the assumption of sphericity had been violated for the interaction effect of response and memory load ($\chi^2(2) = 10.35$, $p < 0.001$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.70$). Response time and load did not interact ($F(1.39, 26.44) = 2.34$, $p = 0.13$).

Table 2.2: Response times in ms and error rates in percentages to the different processing task conditions specified for the different memory loads of experiment 1a.

Variable	Memory Load		
Task Condition	4	6	8
Dual Task SOA 50 ms	RT1: 941 ± 274 ms RT2: 1116 ± 311 ms Errors: 10.83 ± 8.80 %	RT1: 1033 ± 264 ms RT2: 1219 ± 322 ms Errors: 12.18 ± 9.92 %	RT1: 1041 ± 219 ms RT2: 1237 ± 307 ms Errors: 13.00 ± 10.21 %
Dual Task SOA 125 ms	RT1: 976 ± 2323 ms RT2: 1093 ± 276 ms Errors: 13.46 ± 10.38 %	RT1: 1105 ± 252 ms RT2: 1114 ± 283 ms Errors: 12.76 ± 10.76 %	RT1: 992 ± 229 ms RT2: 1244 ± 322 ms Errors: 13.90 ± 12.40 %
Dual Task SOA 200 ms	RT1: 1022 ± 245 ms RT2: 1053 ± 307 ms Errors: 13.89 ± 11.93 %	RT1: 999 ± 212 ms RT2: 1034 ± 256 ms Errors: 11.27 ± 13.36 %	RT1: 1029 ± 223 ms RT2: 1088 ± 314 ms Errors: 11.73 ± 10.81 %
Single Task AUD	RT1: 715 ± 194ms Errors: 4.17 ± 4.48 %	RT1: 765 ± 166 ms Errors: 4.38 ± 4.96 %	RT1: 841 ± 166 ms Errors: 4.17 ± 5.74 %
Single Task VIS	RT1: 601 ± 153 ms Errors: 8.13 ± 8.05 %	RT1: 653 ± 135 ms Errors: 5.21 ± 6.47 %	RT1: 699 ± 91 ms Errors: 7.42 ± 7.14 %

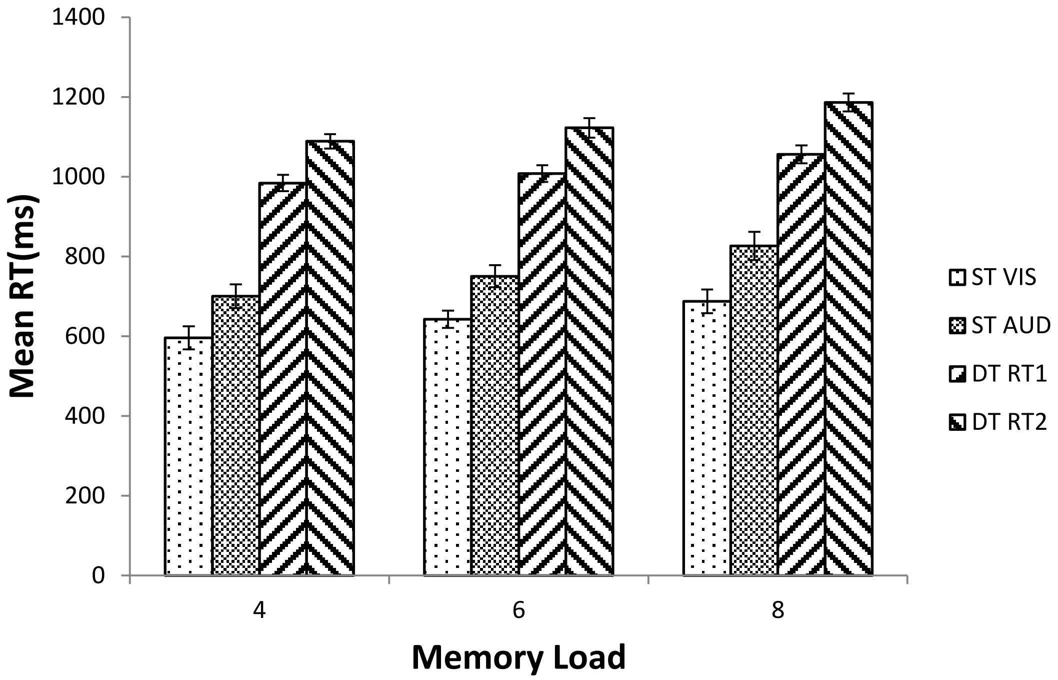


Figure 2.6: Mean response times for the different processing task conditions per memory load of Experiment 1a. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

Another parameter that can be studied is the dual-task costs, e.g. the prolongation of response times. These costs can be calculated for RT1 and for RT2 of the dual-task condition. Since the RT1 for DT is always the response time for the auditory task, the costs can be calculated in the following way: DT-RT1 costs = DT RT1 – RT ST AUD. The RT2 for DT is always the response time for the visual task and therefore DT-RT2 costs = DT RT2 – RT ST VIS. Results showed that there were no significant differences in dual-task costs on either RT1 or on RT2 for the different memory loads (all $t(19) < 1.53$, $p > 0.14$).

Errors. We conducted a 2x3 repeated-measures ANOVA with factors processing task (single, dual-task) and memory load (4, 6, 8 letters) to test whether the error rates for the different tasks and loads were different (Table 2.2, Figure 2.7). The main effect of processing task was significant ($F(1, 19) = 33.65$, $p < 0.001$). Participants made significantly more errors in the dual-task condition (12.33 ± 7.65 %) compared to the single task condition (5.67 ± 4.65 %) for each memory load individually (all $t(19) > 3.89$, $p < 0.001$). This could indicate that there was a partial speed-accuracy trade-off due to slightly slower response times and higher error rates in the dual-task condition. Mauchly's test indicated that the assumption of sphericity had been violated for the main effect of load ($\chi^2(2) = 7.45$, $p < 0.03$). Therefore, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.75$). Results showed that the main effect of memory load was not significant ($F(1.49, 28.38) = 0.53$, $p = 0.54$) indicating that differences in error rates across loads was not significant. Processing task and memory load did not interact ($F(2, 38) = 0.62$, $p = 0.54$). Together, these results on error rates indicate that participants performed well in the task block and did focus on the task block but they spend more time on the task when the memory load increased potentially in order to rehearse the letters to increase their recall performance.

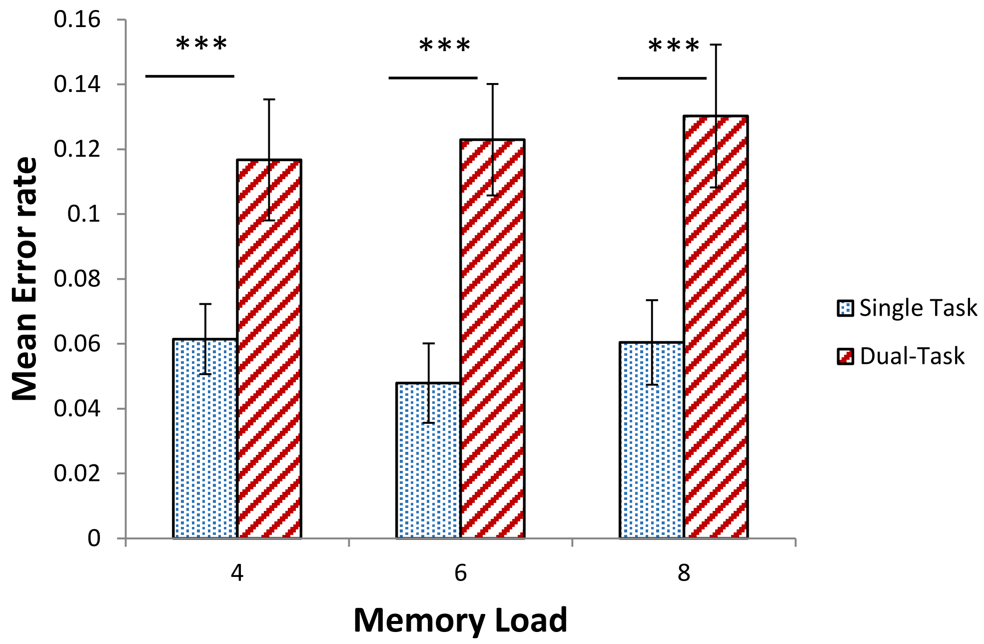


Figure 2.7: Error rates per processing task of Experiment 1a. Error bars denote 95% confidence intervals (Loftus and Mason, 1994). Results of paired samples t-tests for error rate differences are shown above each pair of bars per memory load (* p < 0.001).**

2.2.3 Discussion

The results of the first experiment indicate that when combining a PRP dual-task with a complex WM span task we found no evidence that performing either a dual-task and single task during the retention interval differentially affected recall at any memory load. This occurred despite participants demonstrating the classical PRP effect in processing task performance during the retention interval. Taken together, the results of experiment 1a were not as expected as there was no significant difference between memory performance of the single and dual-task retention interval conditions. There might be a couple of reasons for these findings. First, the high percentages of correctly recalled letters in the dual-task condition for the different memory loads (Table 2.1) indicate that even in the dual-task condition participants had enough time to rehearse the letters. Secondly, participants did not keep performance in the dual-task constant, but instead accepted decreased task (single or dual) task performance with increased memory load to maintain a high performance level in the memory task (Table 2.2). The next experiment was designed to address these issues.

2.3 Experiment 1b: PRP paradigm with memory loads of 5, 6 and 7 letters

This experiment was similar to experiment 1a and again consisted of a memory encoding task, followed by a retention interval with the processing tasks (ST-VIS, ST-AUD or DT) and at the end a recall phase. However, changes were made to fine-tune the experiment and to tackle the issues described in experiment 1a. In experiment 1a participants had enough time in the dual-task condition to rehearse the letters. To increase the demands on the retention interval and reduce rehearsal, the participants were put under more time pressure during the processing tasks by making each trial in the retention interval last only 2.5 seconds instead of 4 seconds. Additionally, the number of trials in the retention interval was reduced from eight to five and the amount of letters to be recalled was changed to 5, 6 or 7 letters. Additionally, in experiment 1a participants accepted decreased task block performance with increased memory load to maintain performance levels in the memory task. This issue was addressed by modifying the instructions and giving the participants feedback on their performance in the retention interval after each memory trial. This ensured that participants prioritized the processing tasks in the retention interval over the rehearsal of the letters and also made the retention interval more competitive. This change is in line with the current literature (Foster et al., 2014; Unsworth et al., 2005), namely keeping costs in task performance constant, which is achieved by providing the participants feedback on their task performance. Participants were specifically instructed to have an 80% or higher accuracy rate per retention interval to make sure they kept high performance in the processing tasks. Again, the prediction was that recall performance was poorer when performing a dual-task during the retention interval compared to performing a single task.

2.3.1 Method

2.3.1.1 Participants

Twenty-two (12 female) participants (mean age: 23 years, SD = 2.5, range 20-31 years) gave written informed consent to take part in the study. The study was approved by Brunel University's Department of Life Sciences Ethics Committee and participants received £8 for participation. The information leaflet, consent form, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 1.

2.3.1.2 Tasks

As before, participants performed a complex WM span task with a processing task in the retention interval period. The phases of experiment 1b were the same as experiment 1a but changes were made to the task parameters.

WM Span Task. In experiment 1a participants showed a ceiling effect for memory load 4, recall performance after both single and dual-task conditions almost reached 100% (97.50% and 96.25% respectively) and therefore it was decided that in experiment 1b memory loads of 5, 6 and 7 letters were used.

Retention interval Processing Phase. During the 12.5 second retention interval, participants performed either an auditory single task, a visual single task or both tasks. The fixation cross at the beginning of each trial was reduced from 500 ms to 250 ms. For the auditory single task, the participant had 2000 ms to respond to the stimulus instead of 2500 ms. For the visual single task, the stimulus was either a blue or yellow circle instead of a black triangle or circle) shown on the screen for 250 ms (previously 300 ms). Participants had 2000 ms to press the “left arrow” key with the right index finger in response to a blue circle and the “down arrow” key with the right middle finger in response to a yellow circle. In the dual-task condition the trial duration was 2500 ms instead of 4000 ms and only 5 trials were performed in the retention interval.

Feedback. Participants received specific feedback on their performance in the processing task at the end of each memory trial to ensure that they properly prioritised that task. This feedback aimed to keep accuracy above 80% and the response times below an individual threshold (determined during the practice period). If people failed to meet the performance criteria, they were encouraged to be more accurate and/or faster by written feedback on the screen and also verbally by the experimenter. This feedback aimed to avoid participants trading low performance in the processing task for higher performance in the recall phase. After the recall of letters, a screen showed their speed (the average reaction time of the five trials) in ms and their accuracy (percentage of trials correct). Based on these values, several types of feedback could be given:

1. If a participant made more than 1 error in the five processing task trials (e.g. the accuracy was below 80%), the participant got the message: “You have to be more accurate”.
2. The participant’ reaction time in the practice session was used to calculate an individual performance threshold value. In the practice session each task was practiced twice but only the second session was used to define the average reaction time which was based on 30 trials for each task. The threshold was set at 30% more than this average reaction time. The value of 30% was based on the results of experiment 1a, since on average a participant would only be too slow in about 25-30% of the retention intervals. In the main experimental block if the average reaction time in the five processing task trials

exceeded the practice threshold then the participant would receive the message: "You have to be faster".

3. If the participant was both too slow and made too many errors, the feedback was: "You have to be faster and more accurate".
4. Finally, if the participant's speed was below the cut-off value and no more than one error was made, the feedback was "Well done".

During the main experiment the researcher paid close attention to the performance in the retention interval. In case the participant made a lot of errors, he/she got the feedback "You have to be more accurate", but was also explicitly instructed by the researcher to maintain good performance (Figure 2.2E). This was done to prevent people from having a low performance in the retention interval due to focusing only on rehearsing the letters. During the practice session the feedback was explained to the participant and the participant was instructed that it was important to have an accuracy of 80% of higher. In this way, the participant was instructed to prioritize the processing task and to not sacrifice this accuracy for the memory task. It was emphasised that is important for the participant to perform well in the single or dual-task. Cut-off values were calculated per subject and in most experiments also per task condition.

Procedure. The first three participants performed 60 memory trials (10 dual-task memory trials of each of the three memory loads, and 10 single task (5 auditory and 5 visual) memory trials for each memory load). However, because the experimental run time with this procedure was too long (well above 1 hour in total), the remaining 19 participants performed 48 memory trials (8 dual – and 8 single task memory trials of each memory load). The order of memory trials was individually randomized for each participant. The shortened main experiment lasted about 30 minutes. Before the main study, participants practiced all tasks for approx. 15 min. In total, the experiment lasted about 1 hour per participant.

2.3.2 Results

As in experiment 1a, the impact of dual-task performance on WM was assessed by analysing the recall performance (accuracy) in the memory task. The performance of the single tasks and dual-task was again measured by response times and error rates. In experiment 1b, no participants were excluded.

2.3.2.1 Recall performance.

A 2x3 repeated-measures ANOVA with the factors processing task (single, dual-task) and memory load (5, 6, 7 letters) was conducted on the recall performance. Mauchly's test indicated that the assumption of sphericity had not been violated for any of the effects. The relative recall was significantly higher in the single task (0.73 ± 0.14) as compared to the dual-task condition (0.65 ± 0.16) (main effect of processing task ($F(1, 21) = 12.05$, $p = 0.002$)). This effect was present for all memory loads (all $t(21) > 2.50$, all $p < 0.03$) (Table 2.3, Figure 2.8).

Table 2.3: Relative Recall Performance of experiment 1b as a function of processing task and memory load.

Variable	**Memory Load**		
Processing Task	5	6	7
Single Task	0.82 ± 0.16	0.72 ± 0.17	0.64 ± 0.15
Dual-Task	0.74 ± 0.14	0.65 ± 0.20	0.56 ± 0.20

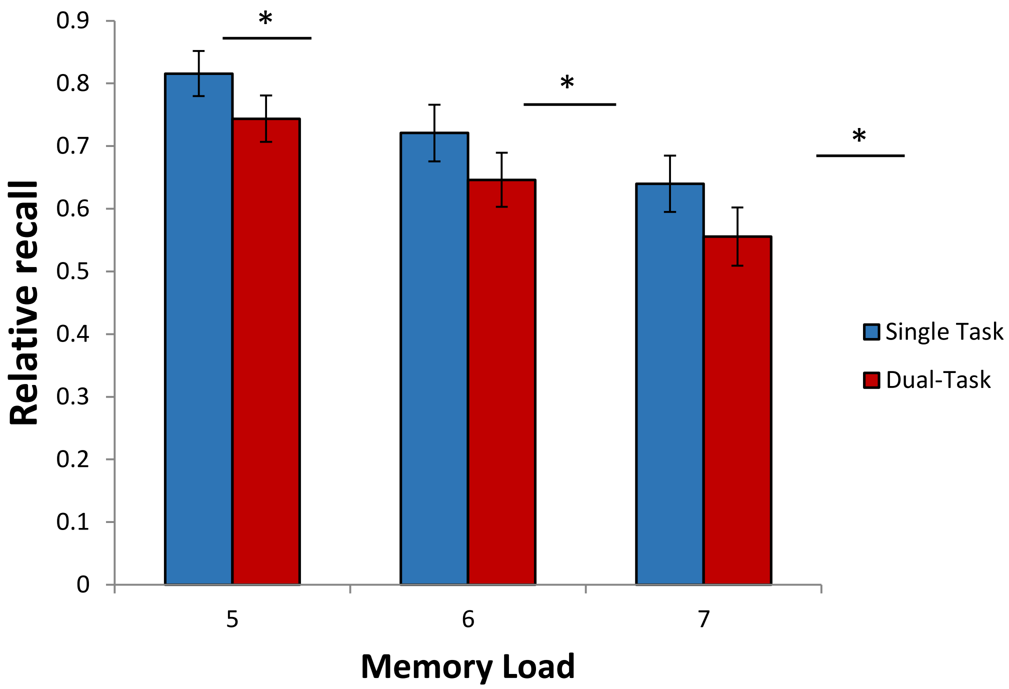


Figure 2.8: Relative recall performance for single task and dual-task conditions of experiment 1b for the three different memory loads. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**. Results of paired t-tests for recall performance differences are shown above each pair of bars of memory load (* $p < 0.05$).**

The relative recall irrespective of task condition, was poorer for higher loads (main effect of memory load: $F(2, 42) = 27.05$, $p < 0.001$). Differences between the different load conditions were analysed with t-tests, which confirmed that all loads differed from each other (all $t(21) > 3.03$, all $p < 0.01$). Processing task and memory load did not interact ($F(2, 42) = 0.08$, $p = 0.92$).

Typically, in complex WM span tasks participants are required to keep performance in the processing task above 80% accuracy. This is to ensure that demands of the processing task affect memory performance and to avoid that participants keep memory performance up by sacrificing performance in the processing task. However, in the current study, we found no evidence for such a trading in. First, in the dual-task condition (as compared to the single task condition), performance was significantly lower on both measures, i.e. memory recall and task performance. Two participants showed accuracy below 80% in the dual-task (while all were above 80% in the single-tasks). However, if at all, the effect on memory performance then was slightly underestimated. The overall pattern of results did not change when the two participants were excluded from the analysis.

2.3.2.2 Processing Task performance

Performance in the processing tasks which were presented during the retention interval was analysed by response times and error rates. In the dual-task participants always had to respond to the auditory stimulus first. This analysis focused on the existence of the PRP effect demonstrating that a central attentional bottleneck was present, which may have required additional executive functions for active scheduling of the tasks. The PRP effect is reflected in an increasing RT2 with decreasing SOA while RT1 is rather independent of the SOA.

Response times. A 2x3 repeated-measures ANOVA with the factors response (RT1, RT2) and SOA values (50, 125 and 200 ms) was conducted to determine the presence of the PRP effect. Mauchly's test indicated that the assumption of sphericity had not been violated for any of the effects. Analysis revealed a typical PRP effect in the DT condition (Figure 2.9). The main effect of response was significant ($F(1, 21) = 13.00$, $p = 0.002$) showing that RT2 is slower than RT1 for all SOAs. Also, the main effect of SOA was significant ($F(2, 42) = 9.78$, $p < 0.001$). In addition, response and SOA interacted ($F(2, 42) = 457.43$, $p < 0.001$). To understand this interaction in more detail, two follow-up one-way repeated-measures ANOVAs were conducted for each task response time (RT1, RT2) separately. Results showed that the RTs on the second task (RT2) significantly increased with decreasing SOA ($F(2, 42) = 37.43$, $p < 0.001$), while the RTs of the first task (RT1) remained roughly constant over the range of SOAs ($F(2, 42) = 1.25$, $p = 0.30$). Follow-up paired t-tests showed that RT2 significantly increased with decreasing SOA (RT2 of shortest SOA (50 ms) (988 ± 172 ms), RT2 of longest SOA (200 ms) (851 ± 163 ms) (all $t(21) > 3.32$, $p < 0.003$) (Figure 2.9).

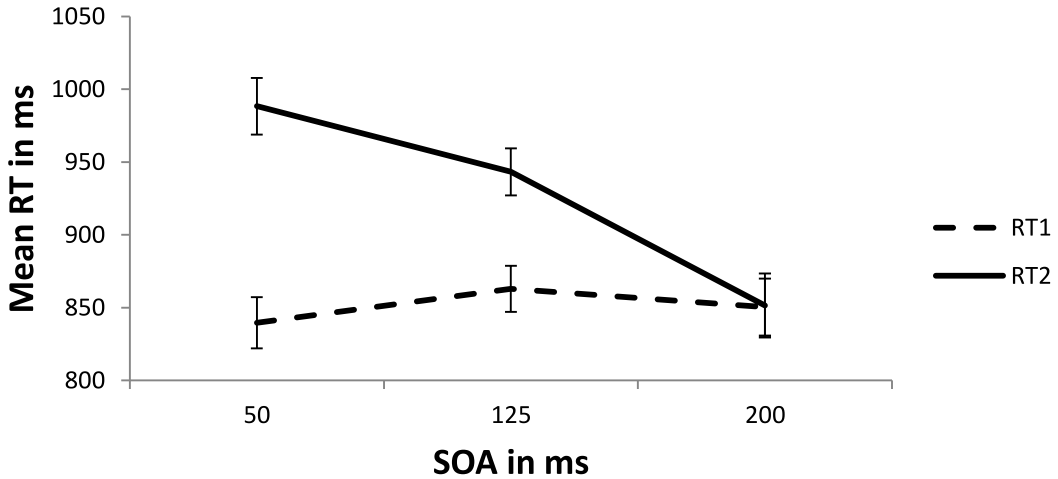


Figure 2.9: PRP effect for experiment 1b, i.e. RT2 (solid line) increases with decreasing SOA whilst RT1 (dotted line) remains roughly constant for different SOAs. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

The classic PRP effect was shown for all memory load conditions by prolonged response times to the second stimulus with decreasing SOA, indicating that indeed a bottleneck occurred in the processing of the PRP dual-task (Figure 2.10).

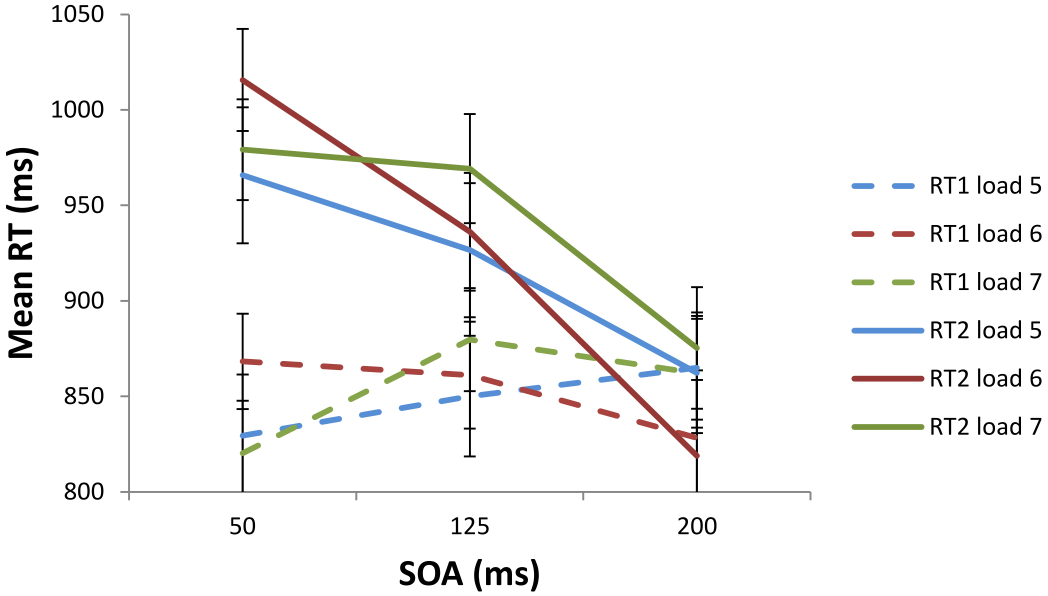


Figure 2.10: PRP effect for experiment 1b for the three different memory loads, i.e. RT2 (solid lines) increases with decreasing SOA whilst RT1 (dotted lines) remains roughly constant for different SOAs. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

To test whether the memory load affected the response times a 2x3 repeated measures ANOVA with the factors response (RT1, RT2) and memory load (5, 6, 7 letters) was conducted (

Table 2.4, Figure 2.11). Due to the PRP effect, RT2 in the dual-task (929 ± 168 ms, always visual task) was significantly longer than the RT1 in the dual-task (851 ± 156 ms, always auditory task) (main effect response: $F(1, 21) = 12.81$, $p = 0.002$) and this was true for each memory load (all $t(21) > 3.24$, $p < 0.004$). The main effect of memory load was not significant ($F(2, 42) = 0.47$, $p = 0.63$), indicating that memory load did not have an effect on either RT1 or RT2 which is line with our prediction. Mauchly's test indicated that the assumption of sphericity had been violated for the interaction effect of response and memory load ($\chi^2(2) = 8.71$, $p < 0.02$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.74$). Response and memory load did not interact ($F(1.48, 31.04) = 3.35$, $p = 0.061$) but may indicate a trend namely that the difference between RT2 and RT1 increases with memory load.

Table 2.4: Response times in ms and error rates in percentages to the different processing task conditions specified for the different memory loads of experiment 1b.

Variable	**Memory Load**		
Processing Task	**5**	**6**	**7**
Dual Task – SOA 50 ms	RT1: 829 ± 180 ms RT2: 965 ± 196 ms Errors: 9.87 ± 8.99 %	RT1: 868 ± 161 ms RT2: 1015 ± 180 ms Errors: 9.17 ± 10.60 %	RT1: 820 ± 146 ms RT2: 979 ± 168 ms Errors: 11.31 ± 9.31 %
Dual Task – SOA 125 ms	RT1: 850 ± 172 ms RT2: 926 ± 190 ms Errors: 13.48 ± 8.82 %	RT1: 861 ± 189 ms RT2: 936 ± 180 ms Errors: 14.17 ± 11.27 %	RT1: 879 ± 188 ms RT2: 969 ± 217 ms Errors: 9.95 ± 7.01 %
Dual Task – SOA 200 ms	RT1: 864 ± 179 ms RT2: 862 ± 202 ms Errors: 13.89 ± 11.93 %	RT1: 828 ± 145 ms RT2: 818 ± 167 ms Errors: 13.16 ± 10.83 %	RT1: 862 ± 169 ms RT2: 875 ± 171 ms Errors: 13.48 ± 13.10 %
Single Task – AUD	RT1: 534 ± 74 ms Errors: 3.91 ± 4.14 %	RT1: 561 ± 86 ms Errors: 3.86 ± 6.97 %	RT1: 570 ± 91 ms Errors: 4.27 ± 5.63 %
Single Task – VIS	RT1: 478 ± 90 ms Errors: 8.45 ± 6.57 %	RT1: 491 ± 89 ms Errors: 7.50 ± 7.61 %	RT1: 495 ± 90 ms Errors: 9.68 ± 8.43 %

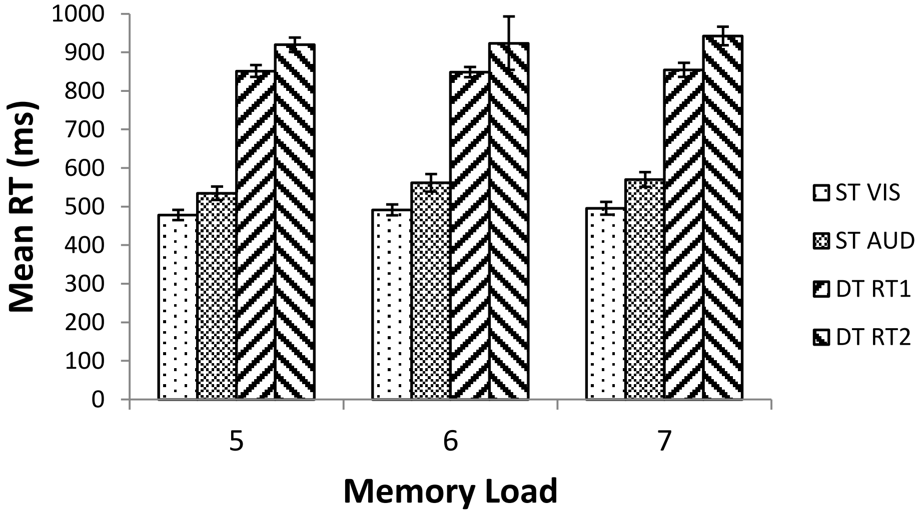


Figure 2.11: Mean response times for the different processing task conditions per memory load of experiment 1b. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

Errors. To test whether the error rates for the different tasks and loads varied a 2x3 repeated measures ANOVA with the factors processing task (single, dual-task) and memory load (5, 6, 7 letters) was conducted (

Table 2.4, Figure 2.12). Mauchly's test indicated that the assumption of sphericity had not been violated for any effects. Results showed no significant difference in error rates across loads (main effect of memory: $F(2, 42) = 0.14$, $p = 0.87$). The main effect of processing task was significant ($F(1, 21) = 37.38$, $p < 0.001$). Participants made significantly more errors in the dual-task condition (12.08 ± 6.41 %) compared to the single task condition (6.28 ± 4.41 %) which was true for each memory load individually (all $t(21) > 4.10$, $p < 0.001$). This indicated that the dual-task related RT increases were not likely due to a speed-accuracy trade-off, but could be partially true. Processing task and memory load did not interact ($F(2, 42) = 1.27$, $p = 0.29$).

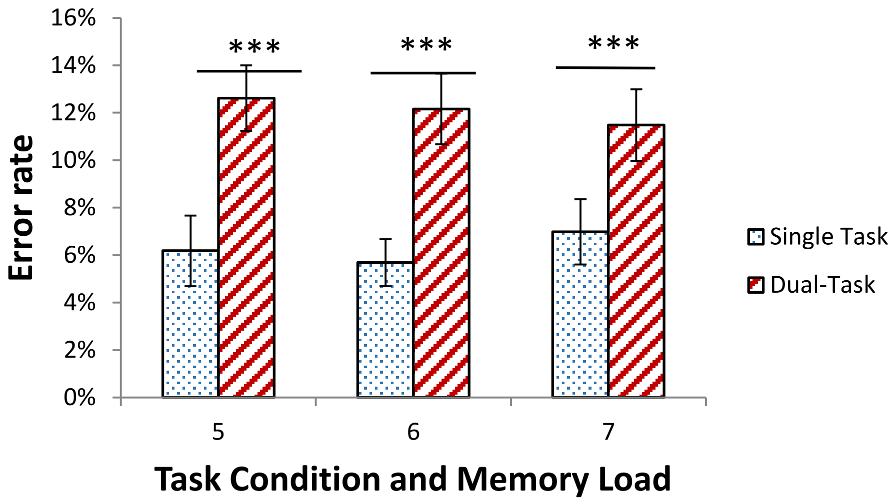


Figure 2.12: Error rates per processing task of experiment 1b. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**. Results of paired samples t-tests for error rate differences are shown above each pair of bars per memory load (*** p < 0.001).**

2.3.3 Discussion

Combining a PRP dual-task with a short-term memory task to create a novel complex WM span task showed that across all memory loads recall performance was lower after performing a dual-task during the WM retention period compared with performing a single task. In addition, we observed a PRP effect, i.e. an SOA dependent slowing of the second response time, which indicates that a processing bottleneck has been present. The error rate results indicated that participants performed well in the processing task and so did not greatly trade off performance in that task to increase recall performance.

Our findings show that PRP dual-tasks and WM are related, because dual-task performance affected memory recall stronger than single-task performance. The TBRS model suggests that this relation is due to the common demands on the limited resource of controlled attention, i.e. executive functions (Barrouillet & Camos, 2007). This interpretation is in line with the active scheduling account of bottleneck processing (De Jong, 1995; Luria & Meiran, 2003). Furthermore, our findings suggest that the additional processes involved in coordinating task processing at the stage of the bottleneck, such as inhibition, switching, and monitoring, are closely related or even identical to the executive functions of WM. Further discussion can be found in Chapter 4 which discusses all behavioural studies together.

The next chapter aims at manipulating the difficulty of the dual-task condition to further investigate this relationship between PRP dual-tasks and WM.

Chapter 3 : The effect of order manipulations in the PRP dual-task on recall performance

3.1 Introduction

Experiment 1 employed the logic of cognitive subtraction and compared dual-task with single task performance to identify dual-task specific demands on executive functions. However, in addition to imposing higher demands on executive functions dual-task performance may also affect short-term memory. This is, because in dual-task conditions participants must maintain two active stimulus-response mappings at the same time (one for each component task), while they only have to maintain one in single task blocks. To circumvent this, experiment 2 used a parametric manipulation approach in which we compared two dual-task conditions which gradually differed in their demands on controlled attention (cf. Szameitat, Schubert, Müller, & von Cramon, 2002). In more detail, we manipulated the demands on task-order scheduling (Schubert, Fischer, & Stelzel, 2008) by having participants either respond in a constant, or in a randomly varying, order to the component tasks.

The manipulation is based on findings from De Jong (1995) who showed that the difficulty of a PRP dual-task can be manipulated by varying the order in which the component tasks have to be processed (but see also Luria & Meiran, 2003). In more detail, in PRP dual-tasks, participants typically respond to the component tasks in a given order, which is usually the order in which the tasks have been presented. Research of De Jong (1995) has shown that participants automatically prepare to respond in the same order as they did in the previous trial (e.g. AB, AB, AB; A and B denoting the component tasks), and that if the order changes (e.g. AB, BA, AB) response times and error rates are increased.

These behavioural costs in order-change (switch-order) trials arise because participants need to overcome the incorrectly prepared task order. In more detail, in order-change trials the task which originally was prepared to be processed first needs to be inhibited, and the bottleneck needs to be switched from the expected first task to the actual first task (De Jong, 1995; Luria & Meiran, 2003). Thus, order-change trials impose higher demands on the same executive functions, i.e. switching and inhibition, which are already involved in the active scheduling of task processing at a bottleneck anyway. Consequently, we predicted that order-change trials impair the concurrent maintenance of items in short-term memory more than same-order trials.

Except for minor changes, experiment 2 used the same design and stimuli as experiment 1b, i.e. we used a complex WM span task with preload procedure and varied the nature of the processing task which had to be performed during the retention interval. The processing tasks were two dual-task conditions, one with a randomly varying order of the component tasks and one with a fixed task order. We expected recall performance to be lower in the random compared to the fixed processing task.

3.2 Experiment 2a: Pilot 1

3.2.1 Method

3.2.1.1 Participants

For the pilot study eight (4 female) participants (mean age: 22.9 years, SD = 2.9, range 20-29 years) took part in the study after given written informed consent. The study was approved by Brunel University's College of Health and Life Science Ethics Committee and participants received £8 for participation. The information leaflet, consent form, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 2.

3.2.1.2 Tasks

Again a complex WM span task was used with preload procedure which consisted of the following phases: cue, memory encoding phase, retention interval processing phase, recall phase and feedback. The tasks in the retention interval consisted of fixed conditions (tone -> colour and colour -> tone) and random conditions (random 1 (few switches) and random 2 (more switches)). Only the recall phase was the same as experiments 1, the other phases were changed as described below.

Cue. The cue was the same as in experiment 1 but it was displayed for 3 seconds instead of 5 seconds informing the participant about the upcoming trial. This could be either "Tone -> Colour" or "Colour -> Tone" for the fixed-order conditions or "Random Order 1" or "Random Order 2" for the random-order conditions.

Memory Encoding Phase. In this experiment, only one memory load of 6 letters was used.

Retention Interval Processing Phase. After the memory encoding phase, a 16.8 seconds retention interval was presented, during which participants performed one of the three orders of the processing task, i.e. fixed, random 1 or random 2 condition. During the retention interval participants performed 6 trials each lasting 2800 ms, which was increased compared with experiment 1b (2500 ms) because of the greater task difficulty in the random condition. In the main experiment, only dual-task blocks were presented and the single tasks were only used in the practice session to familiarise participants with the response mappings.

Feedback. This component was the same as in experiment 1b. At the end of each memory trial, participants received feedback about their performance in the retention interval which aimed at keeping accuracy above 80%. For the practice, the dual-task blocks were divided into fixed and random conditions and an average reaction time of the practice session of these 2 types of blocks was used to calculate the cut-off values to which the average time of the task block (6 trials) in the main experiment was compared to.

Processing tasks.

Auditory Single Task. This component was the same as experiment 1b except that the participant had 2300 ms to respond.

Visual Single Task. This component was similar to experiment 1b except that the participant had 2300 ms to respond and the visual stimulus (the blue or yellow circle) was presented in a different way. The circle was presented in a frame and could be presented at one of the four locations as is shown in Figure 3.1.

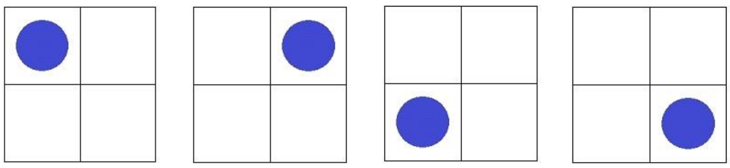


Figure 3.1: Four different presentations of the visual stimulus for experiment 2a.

Dual-task. This component was similar to experiment 1b except the order in which participants should respond to the tasks could change and so the participant had 2300 ms to respond (instead of 2000 ms) to allow for the increased difficulty. There were 6 different order conditions in the dual-task but the auditory and visual stimuli were presented at the same time (i.e. SOA 0 ms). The visual stimulus, the circle, was presented in a frame as mentioned above and the position of the circle determined the order in which the participants needed to respond to the stimuli. If the circle appeared on the right side of the frame, the participant had to respond to the auditory stimulus first and then to the visual stimulus (see the left panel of Figure 3.2). If the circle appeared on the left side of the frame, the participant had to respond to the visual stimulus first and only then to the auditory stimulus as shown in the right panel of Figure 3.2.

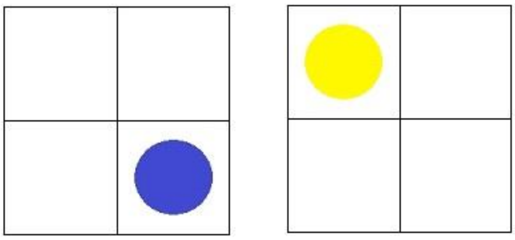


Figure 3.2: ***Left:*** **The visual stimulus is shown on the right side of the frame, so the participant first had to respond to the auditory stimulus, followed by the visual stimulus.** ***Right:*** **The visual stimulus is shown on the left side of the frame, so participants had to first respond to the visual stimulus, followed by responding to the auditory stimulus.**

Each of the 6 different order conditions is illustrated but for simplicity only the blue circle stimulus is shown. Condition 1 (“Fixed condition”) consisted of a pure auditory-visual (“Tone -> Colour”, “TC”) condition in which participants first had to respond to the auditory stimulus followed by the visual stimulus, thus in the same way as in experiment 1 (Figure 3.3). As is shown in the figure 3.3, the circle is always on the right side of the frame and is randomly located up and down.

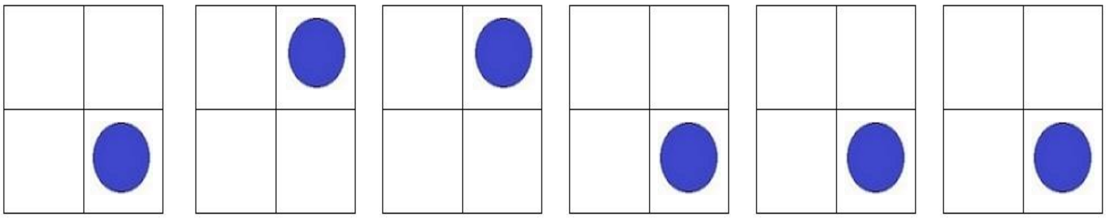


Figure 3.3: Possible visual stimuli locations for each trial in Condition 1: “Tone -> Colour”. The location of the circle is randomly one of the two locations on the right side of the frame.

Condition 2 (“Fixed condition”) was a pure visual-auditory (“Colour -> Tone”, “CT”) condition in which participants first had to respond to the visual stimulus followed by responding to the auditory stimulus. The circle is always on the left side of the frame and moves randomly up and down per trial (Figure 3.4).

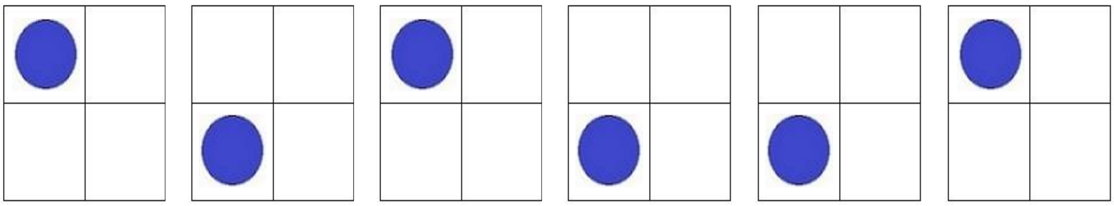


Figure 3.4: Possible visual stimuli locations for each trial in Condition 2: “Colour -> Tone”. The location of the circle is randomly one of the two locations on the left side of the frame.

Condition 3 and 4 (“Random Order 1”) was a pseudo-random processing task condition with a few switches between the two different response orders. The circle moved in a particular way through the frame as is shown in Figure 3.5. The sequence of response order was “TC”, “TC”, “CT”, “CT”, “TC”, “TC” for condition 3 and counterbalanced for condition 4, so “CT”, “CT”, “TC”, “TC”, “CT”, “CT”.

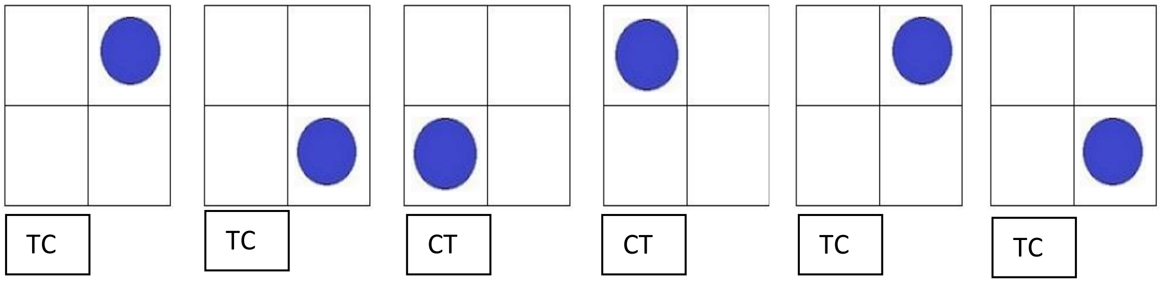


Figure 3.5: Visual stimuli sequence for condition 3 (“Random Order 1”). The circle moved in a systematic way from one part of the frame to another. This sequence was counterbalanced for condition 4 (“Random Order 1”).

Conditions 5 and 6 (“Random Order 2”) was a pseudo-random processing task condition with more switches between the two different response orders. The circle stayed in the upper part of the frame and moved from left to right alternating between tone -> colour and colour -> tone (Figure 3.6). The sequence of response order was “TC”, “CT”, “TC”, “CT”, “TC”, “CT” for condition 5 and counterbalanced for condition 6, so “CT”, “TC”, “CT”, “TC”, “CT”, “TC”.

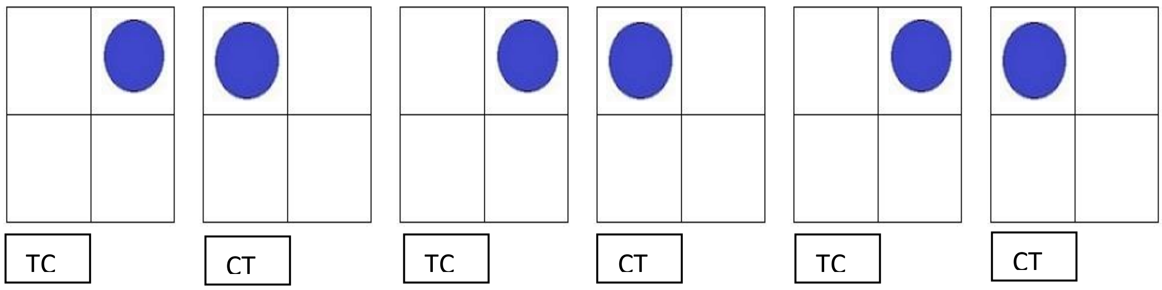


Figure 3.6: Visual stimuli sequence for condition 5 (“Random Order 2”). The circle moved in a systematic way from left to right in the upper part of the frame and therefore alternated between tone -> colour and colour -> tone. This sequence was counterbalanced for condition 6 (“Random Order 2”).

Procedure. Each participant performed 36 memory trials (6 per condition), all having 6 letters as a memory load. Before the main study, participants practiced all tasks (including the single tasks) for approx. 20 min. The random dual-task conditions were practiced extensively since they are perceived to be more difficult and it is important that participants have high accuracy levels in these tasks before they move on to the memory trials in the main experiment. The main experiment lasted about 30 minutes. The first seven participants in the pilot performed 36 memory trials in total. However, for these participants the experiment lasted about 1.5 hours in total and therefore it was decided to cut down the number of repetitions to 30 memory trials, making the total experiment last about 1 hour.

3.2.2 Results

Due to a technical error, the data for participant 1 was excluded from the data analysis. In the analyses the fixed condition is the average of conditions 1 and 2, random low is the average of conditions 3 and 4 and random high is the average of conditions 5 and 6. No participants were detected as outliers.

3.2.2.1 Recall performance

To test whether the order manipulation affected memory recall, the relative recall between the fixed and random processing task conditions was compared by using a one-way repeated-measures ANOVA with 3 levels (fixed, random low and random high) (Figure 3.7). Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(2) = 6.49$, $p = 0.039$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.58$). The relative recall was not significantly different between the fixed and random processing task conditions, fixed (0.73 ± 0.14), random low (0.69 ± 0.25) and random high (0.70 ± 0.20) ($F(1.16, 6.95) = 0.33$, $p = 0.62$).

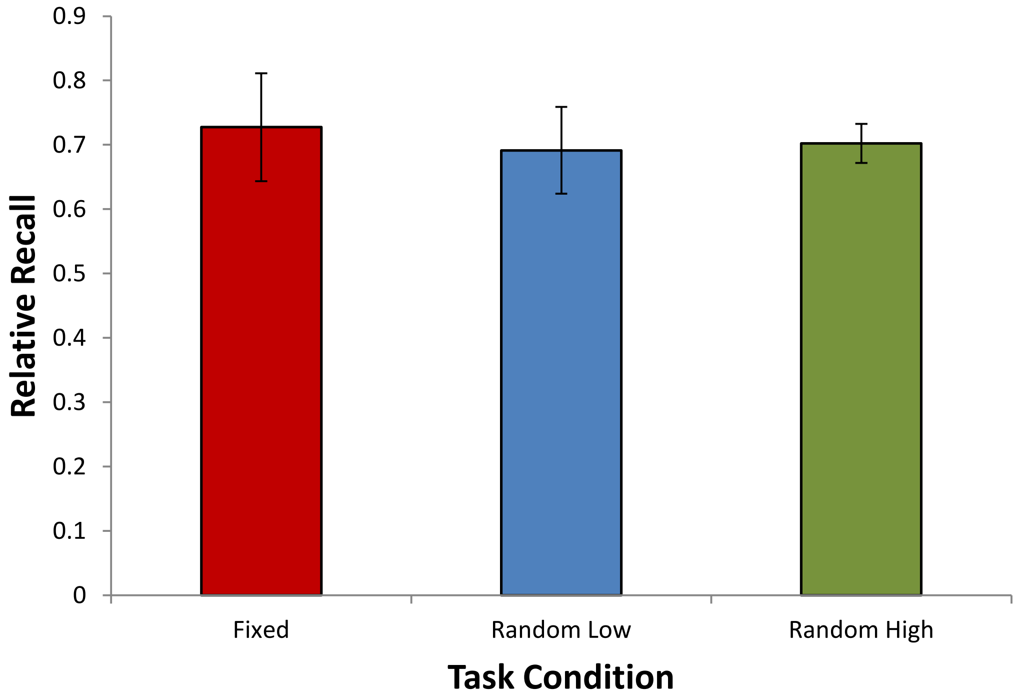


Figure 3.7: Relative recall performance for fixed and the two random conditions of experiment 2a. Error bars denote 95% confidence (Loftus & Masson, 1994)**.**

3.2.2.2 Processing task performance

Performance in the retention interval processing tasks was analysed in terms of response times and error rates.

Response times. A 2x3 repeated-measured ANOVA with factors response (RT1, RT2) and processing task (fixed order, random low and random high) was conducted to analyse the response times for all task types (Table 3.1, Figure 3.8). Mauchly's test indicated that the assumption of sphericity had not been violated for any of the effects. The main effect of response was significant ($F(1,6) = 54.60$, $p < 0.001$). Follow-up t-tests showed that the RT2s of each of the three dual-task conditions (fixed order, random low and random high) were significantly longer than their respective RT1s (all $t(6) > 6.85$, all $p < 0.001$). The main effect of processing task was significant ($F(1,6) = 12.84$, $p = 0.012$). Follow-up t-tests showed that this difference was attributable to statistically differences in both the RT1s and RT2s between fixed and random high conditions and between random low and random high conditions (all $t(6) > 3.11$, $p < 0.03$). The RTs (RT1 and RT2) differences between the fixed and the random low condition were not significantly different for either RT1 ($t(6) = 2.38$, $p = 0.054$) or RT2 ($t(6) = 1.73$, $p = 0.13$) (Table 3.1). There was no interaction between response time and processing task ($F(1,6) = 0.27$, $p = 0.62$).

Table 3.1: Response times in ms and error rates in percentages of the different task conditions of experiment 2a.

Variable	**RT in ms**		**Error rate in %**
Processing Task	RT1	RT2	
Fixed	1063 ± 197	1336 ± 157	14.52 ± 13.13
Random Low	1114 ± 214	1387 ± 196	9.21 ± 6.67
Random High	1208 ± 223	1468 ± 212	16.79 ± 13.04

Errors. To test whether the error rates were different between the dual-task conditions, a one-way repeated-measures ANOVA with 3 levels (fixed, random order low and random order high) was conducted (Table 3.1, Figure 3.8). Mauchly's test indicated that the assumption of sphericity had been violated for the effect of processing task on error rates ($\chi^2(2) = 6.49$, $p = 0.039$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.58$). The error rates did not differ significantly between the fixed and random processing task conditions, fixed (14.52 ± 13.13), random low (9.21 ± 6.67) and random high (16.79 ± 13.04 %) ($F(1.16, 6.95) = 3.38$, $p = 0.11$).

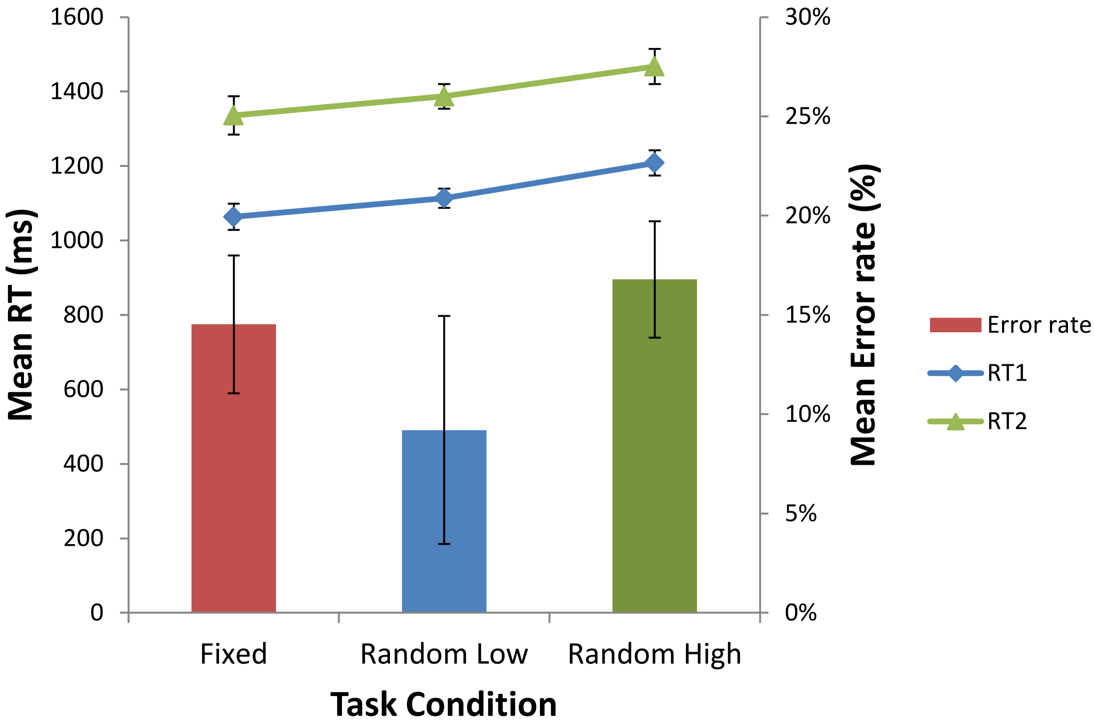


Figure 3.8: Mean response times (left axis, lines) and error rates (right axis, bars) for each dual-task condition of experiment 2a. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

3.2.3 Discussion

Overall, in this pilot it became clear that presenting the different random conditions by moving the circle in the frame was not effective. The fixed condition appeared to be quite difficult for participants (large reaction times and large errors (even larger than the random low condition)). A larger difference in reaction time between the fixed and random condition was needed to separate these two conditions from one another and to get a difference in recall performance. Therefore, the visual stimulus was changed and experiment 2b was designed.

3.3 Experiment 2b: Pilot 2

The pilot study did not show a significant difference between the recall performance of the fixed and random conditions and participants found it difficult to determine the response order based on the position of the circle in the frame. Hence, the visual stimulus was changed. Except for minor changes, experiment 2b used the same design as experiment 2a. A complex WM span task with preload procedure was used and the nature of the processing task performed during the retention interval was varied. The processing tasks were again three dual-task conditions, one fixed order condition (either tone -> colour, or colour -> tone) and two random conditions (one with low switches and one with high switches). Recall performance in the random conditions (lowest in the high switches condition) was expected to be lower than the fixed processing task.

3.3.1 Method

3.3.1.1 Participants

Twenty-one (11 female) participants (mean age: 23.4 years, SD = 4.0, range 19-31 years) took part in the study after given written informed consent. The study was approved by Brunel University's College of Health and Life Science Ethics Committee and participants received £8 for participation. The information leaflet, consent form, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 2.

3.3.1.2 Tasks

Again a complex WM span task was used with preload procedure which consisted of the following phases: cue, memory encoding phase, retention interval processing phase, recall phase and feedback. The tasks in the retention interval consisted of fixed conditions (tone -> colour and colour -> tone) and random conditions (random 1 (low switches) and random 2 (high switches)).

The cue, memory encoding phase, recall phase and feedback were largely the same as experiment 2a. The only item that was changed was the way in which the participants were informed about the order of the stimuli. A frame around the visual stimulus was used to indicate the order in which participants had to respond to the stimuli (Figure 3.9). If there was a square around the circle, the participant first had to respond to the tone and then to the colour of the circle. If there was a diamond around the circle, the participant first had to respond to the colour of the circle and then to the tone. For illustration purposes only the yellow circle is shown (see figure 3.9).

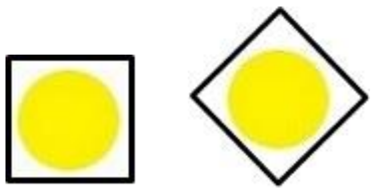


Figure 3.9: Visual stimuli for experiment 2b. The shape around the circle indicated the order in which the participants had to respond to both stimuli. Square indicated tone->colour whilst diamond indicated colour->tone.

<u>Processing tasks.</u> Again, there were 6 different order conditions in the dual-task, the same conditions as in experiment 2a. Condition 1 ("Fixed condition") consisted of a pure auditory-visual ("Tone -> Colour", "TC") block order in which participants first had to respond to the auditory stimulus followed by the visual stimulus. Condition 2 ("Fixed condition") was a pure visual-auditory ("Colour -> Tone", "CT") block in which participants first had to respond to the visual stimulus followed by responding to the auditory stimulus. Condition 3 and 4 ("Random Order 1") consisted of a random processing task block with a low number of switches between the two different response orders. The sequence of response order was "TC", "TC", "CT", "CT", "TC", "TC" for condition 3 and counterbalanced for condition 4, so "CT", "CT", "TC", "TC", "CT", "CT" (Figure 3.10).

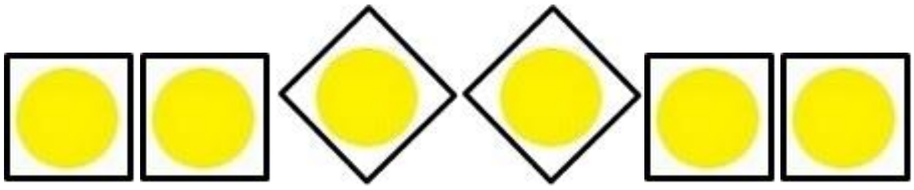


Figure 3.10: Visual stimuli sequence for condition 3 ("Random Order 1"). The circle moved in a systematic way from one part of the frame to another. This sequence was counterbalanced for condition 4 ("Random Order 1").

Conditions 5 and 6 ("Random Order 2") was a random block where the response order was alternated. The sequence of response order was "TC", "CT", "TC", "CT", "TC", "CT" for condition 5 and counterbalanced for condition 6, so "CT", "TC", "CT", "TC", "CT", "TC" (Figure 3.11).

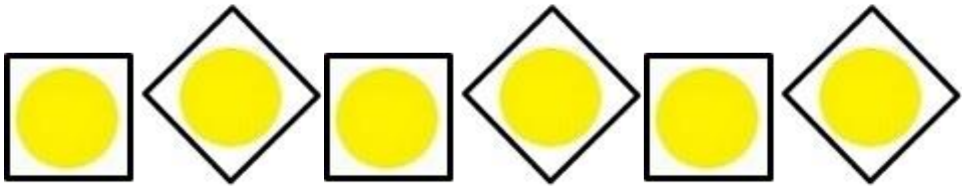


Figure 3.11: Visual stimuli sequence for condition 5 ("Random Order 2"). The circle moved in a systematic way from left to right in the upper part of the frame and therefore alternated between tone->colour and colour>tone. This sequence was counterbalanced for condition 6 ("Random Order 2").

Procedure. Thirty memory trials (5 per condition), all having 6 letters as a memory load, was the procedure in this experiment and the main experiment lasted about 30 minutes. Before the main experiment, participants practiced all tasks (including the single tasks) for approx. 20 min. Again the random dual-task conditions were practiced extensively since they are more difficult and it is important that participants have high accuracy levels in these tasks to be able to perform a concurrent memory task in the main experiment.

3.3.2 Results

In the analyses, the fixed condition is the average of conditions 1 and 2, random low is the average of conditions 3 and 4 and random high is the average of conditions 5 and 6. No participants were excluded.

3.3.2.1 Recall performance

To test whether the order manipulation affected memory recall, the relative recall between the fixed and random processing task conditions was compared by conducting a one-way repeated-measures ANOVA with 3 levels (fixed, random order low and random order high). The relative recall did not differ significantly between the fixed and random processing task conditions, fixed (0.612 ± 0.206), random low (0.607 ± 0.241) and random high (0.613 ± 0.244) ($F(2, 40) = 0.044$, $p = 0.96$ (Figure 3.12).

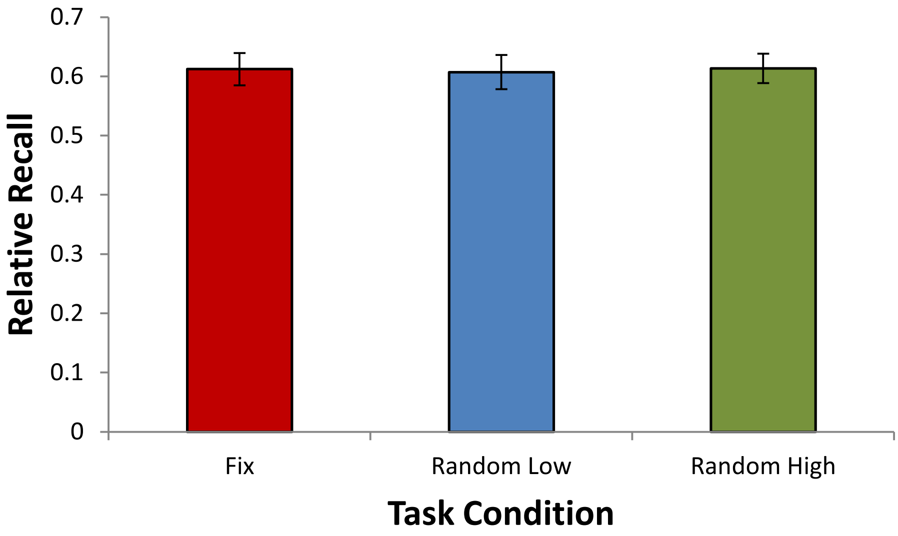


Figure 3.12: Relative recall performance for fixed and the two random conditions of experiment 2b. Error bars denote 95% confidence intervals (Loftus & Masson, 1994).

3.2.2.2 Processing task performance

Performance in the processing tasks which were presented during the retention interval was analysed in terms of response times and error rates.

Response times. A 2x3 repeated-measures ANOVA with factors response (RT1, RT2) and processing task (fixed-order, random low and random high) was conducted to analyse the response times for all dual-task conditions (Table 3.2, Figure 3.13). The main effect of response was significant ($F(1, 20) = 137.67$, $p < 0.001$). Follow-up t-tests showed that the RT1s of each of the three dual-task conditions (fixed order, random low and random high) were significantly shorter than their respective RT2s (all $t(20) > 11.06$, $p < 0.001$). The main effect of processing task was also significant ($F(2, 40) = 61.37$, $p < 0.001$). Follow-up t-tests showed that the RT1s of all conditions significantly differed from each other ($t(20) > 2.53$, $p < 0.02$). In more detail, the RT1s of the fixed condition (1114 ± 148 ms) were significantly shorter than RT1s of the random conditions (average RT1s: 1281 ± 142 ms) ($t(20) = 10.00$, $p < 0.001$). Also, the RT2s of the three conditions significantly differed from another ($t(20) > 2.51$, $p < 0.02$). In more detail, the RT2s of the fixed condition (1349 ± 184 ms) were significantly shorter than the RT2s of the random conditions (average RT2: 1501 ± 170 ms) ($t(20) = 9.25$, $p < 0.001$). Also, both RT1s and RT2s were significantly shorter for the random high conditions compared with the random low condition (all $t(20) > 2.50$, $p < 0.03$). Mauchly's test indicated that the assumption of sphericity had been violated for the interaction effect of response time and processing task ($\chi^2(2) = 7.18$, $p < 0.03$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.76$). Response time and processing task did interact ($F(1.52, 30.43) = 4.98$, $p = 0.02$). All these results show that the fixed and random conditions were clearly different from another in regards to response times.

Table 3.2: Response times in ms and error rates in percentages of the different task conditions of experiment 2b.

Variable	RT in ms		Error rate in %
Processing Task	RT1	RT2	
Fixed	1114 ± 148	1349 ± 184	7.58 ± 5.94
Random Low	1301 ± 152	1519 ± 174	13.03 ± 10.56
Random High	1262 ± 141	1483 ± 174	13.73 ± 12.52

Errors. To test whether the error rates were different between the dual-task conditions, a one-way repeated-measures ANOVA with 3 levels (fixed, random order low and random order high) was conducted (Table 3.2, Figure 3.13). Mauchly's test indicated that the assumption of sphericity had been violated for the effect of processing task on error rates ($\chi^2(2) = 7.052$, $p = 0.029$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.76$). The main effect of processing task condition on errors was significant ($F(1.53, 30.53) = 6.62$, $p = 0.007$). Follow-up t-tests showed that participants made significantly less errors in the fixed condition (7.58 ± 5.94 %) compared to the two random conditions (average error rate: 13.37 ± 11.21 %) (all $t(20) > 2.77$, $p < 0.02$). There was no significant difference between the error rates of random low (13.03 ± 10.56 %) and random high condition (13.73 ± 12.52 %) ($t(20) = 0.55$, $p = 0.58$). This shows that, as expected, participants found the random conditions to be more difficult than the fixed condition. However, participant performance indicates a similar level of difficulty in the two random conditions.

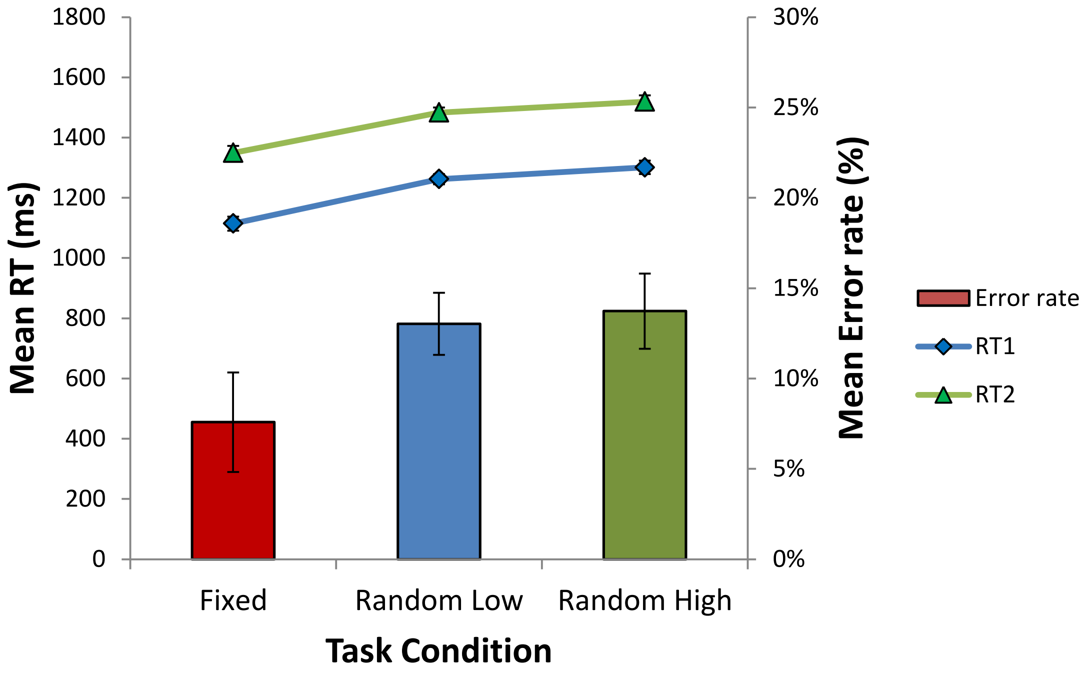


Figure 3.13: Mean response times (left axis, lines) and error rates (right axis, bars) for each dual-task condition of experiment 2b. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

3.3.3 Discussion

There was no significant difference in recall performance between the three processing task conditions. The new way of presenting the different random conditions by using a cue around the circle, either a diamond or a square, was clearer to participants than moving the circle in the frame. However, participant still found it difficult to adapt to the random conditions in the processing task block and hence experiment 2c was designed where pairs of memory trials were used so participants could adapt to the previous memory trial which would make it easier to distinguish between the different processing task conditions (fixed, random low and random high).

3.4 Experiment 2c: Memory trial pairs

Experiment 2b did not show a significant difference between recall performance in fixed and random processing task conditions. Participants often needed one processing task trial to adjust and therefore another experiment was designed with an order manipulation and presented all memory trials in pairs, e.g. “Random”, “Random”, “Tone -> Colour”, “Tone -> Colour”, etc. so that participants had one “practice” to adjust to the specific condition. Except for minor changes, experiment 2c used the same design as experiment 2b. The processing tasks were two dual-task conditions, one with a randomly varying order of the component tasks and one with a fixed order. There was no distinction for the participants between a low number and a high number of switches in the random order conditions as participants found both equally difficult in experiment 2b.

3.4.1 Method

3.4.1.1 Participants

Seventeen (14 female) participants (mean age: 19 years, SD = 2.4, range 18-26 years) took part in the study after having given written informed consent. The study was approved by Brunel University's College of Health and Life Sciences Ethics Committee and participants received course credits for participation. The information leaflet, consent form, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 2.

3.4.1.2 Tasks

The experiment again consisted of a WM task with preload procedure consisting of the following phases: cue, memory encoding phase, retention interval processing phase (fixed or random dual-task), recall phase and feedback. The memory encoding phase, recall phase and feedback were almost the same as experiment 2b. The cue was now shown on the screen for 4 seconds instead of 3 seconds previously. The cue could be either "Tone -> Colour", "Colour -> Tone" for the fixed conditions or "Random" for the random condition. The retention interval was slightly changed.

Retention Interval Processing Phase. This lasted 14 seconds during which participants performed one of the three employed processing tasks. While only dual-tasks blocks were used in the main experiment, the single tasks were used during the practice before the experiment to familiarize with the component tasks. The dual-task conditions (SOA 0 ms) again used the frame (square or diamond) around the circle to indicate the response order. All processing tasks consisted of five (instead of six) trials lasting 2800 ms each. The first condition ("Tone -> Colour", "TC") consisted of a fixed auditory-visual order in which participants responded to the tone and then to the colour of the circle. Condition 2 ("Colour -> Tone", "CT") was a fixed visual-auditory block in which participants responded to the colour of the circle followed by responding to the tone. The third condition ("Random") consisted of a random task block in which the occurrence of the two different orders ("TC" and "CT") was randomized with the restriction that at least two order switches had to be present in each five trial set of processing tasks.

Procedure. There was again only one memory load (6 letters) and two different types of dual-task (fixed and random). The previous experiment (experiment 2b) had shown that participants often find it difficult to adjust to the different processing task conditions. The order of the memory trials was pseudo-randomized, with the restriction that conditions were always presented in pairs, e.g. "Random", "Random", "Tone -> Colour", "Tone -> Colour", etc. Four different pseudo-randomized sequences were created and evenly used across participants. In total, each participant performed 36 memory trials (12 dual-task memory trials of each of the three dual-task conditions, e.g. “TC”, “CT” and “Random”). The main experiment lasted about 25 min. Before this, participants practiced all tasks (including the single tasks) for approx. 25 min.

3.4.2 Results

As described above, the analyses are based only on the 2nd memory trial of each pair and due to a programming error, the data of the first 4 participants only included recall performance of the second memory trial. Again, the impact of dual-task performance on WM was analysed by the recall performance in the memory task. The performance of the dual-tasks was again measured by response times and error rates. No participants were excluded. In these analyses the fixed condition is the average of the “TC” and “CT” conditions.

3.4.2.1 Recall performance

To test whether the order manipulation affected memory recall, the relative recall between the fixed and random processing task conditions was compared using paired-sample t-tests. The relative recall was significantly higher in the fixed (0.58 ± 0.13) as compared with the random condition (0.43 ± 0.22) ($t(16) = 3.46$, $p = 0.003$) (Figure 3.14). To note, the recall performance of the two fixed conditions, “TC” (0.60 ± 0.15) and “CT” (0.56 ± 0.16), did not significantly differ from each other ($t(16) = 1.04$, $p = 0.32$).

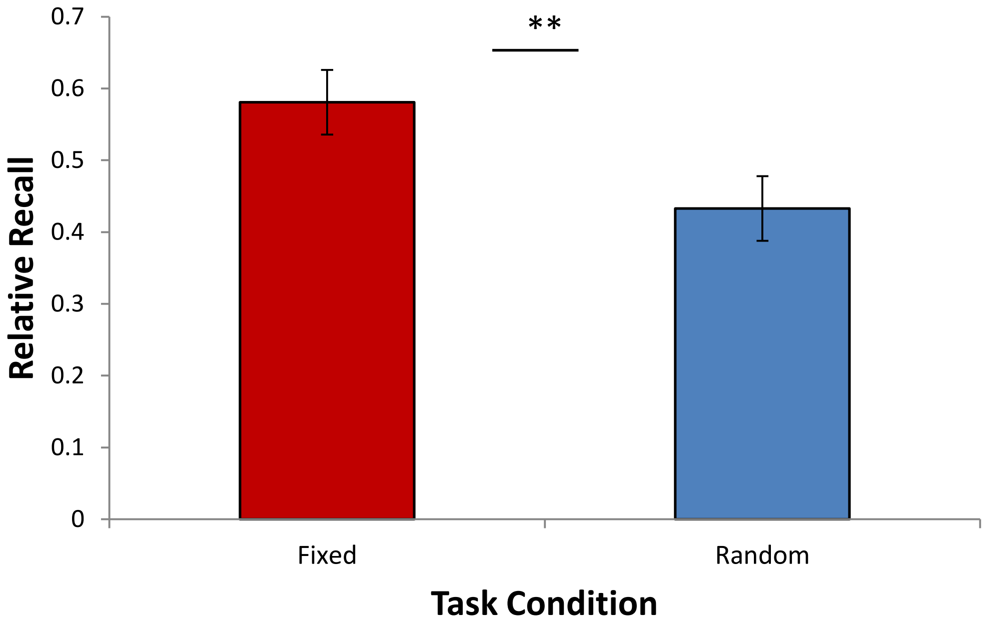


Figure 3.14: Relative recall performance for fixed and random conditions of experiment 2c. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**. Results of paired samples t-tests testing for recall performance differences are shown (** p < 0.01).**

For the first memory trial in each pair, the recall performance of both fixed conditions (“TC”: 0.451 ± 0.166, “CT”: 0.498 ± 0.130) was numerically higher than the random condition (0.447 ± 0.244), reflecting the analyses of the second memory trial. However, here the difference between the fixed and random conditions failed to reach significance ($t(12) = 0.57$, $p = 0.58$). Thus as shown in the second pair in each memory trial, the recall performance of the random condition is lower than the fixed condition, supporting the hypothesis that higher demands on executive functions in a dual-task adversely affects memory performance.

3.4.2.2 Processing Task performance

Performance in the processing tasks presented during the retention interval was analysed using response times and error rates.

Response times. A 2x2 repeated measures ANOVA with the factors response (RT1, RT2) and processing task (fixed, random) was conducted to analyse the response times for both task types (Table 3.3, Figure 3.15). Response times to the second task were significantly slower than those to the first task (main effect of response $F(1, 16) = 151.18$, $p < 0.001$). This effect was present in both the fixed and the random order task conditions (all $t(16) > 10.82$, all $p < 0.001$). The main effect of processing task was significant ($F(1, 16) = 137.37$, $p < 0.001$). Follow-up t-tests showed that both the RT1s (1341 ± 154 ms) and RT2s (1589 ± 156 ms) of the random condition were significantly longer than the RT1s (1030 ± 131 ms) and RT2s (1277 ± 161 ms) of the fixed condition, respectively (all $t(16) > 10.31$, all $p < 0.001$). There was no interaction between response and processing task ($F(1, 16) = 0.01$, $p = 0.92$).

Errors. Participants made significantly more errors in the random condition (17.84 ± 9.42 %) compared with the fixed condition (6.08 ± 2.57 %) ($t(16) = 5.40$, $p < 0.001$) (Table 3.3, Figure 3.15). The analysis of the first memory trial of each pair showed numerically a similar pattern as the 2nd memory trial.

Table 3.3: Response times in ms and error rates in percentages of each dual-task condition of experiment 2c.

Variable	**RT in ms**		**Error rate in %**
Processing Task	RT1	RT2	
Fixed	1030 ± 131	1341 ± 154	6.08 ± 2.57
Random	812 ± 142	1589 ± 156	17.84 ± 9.42

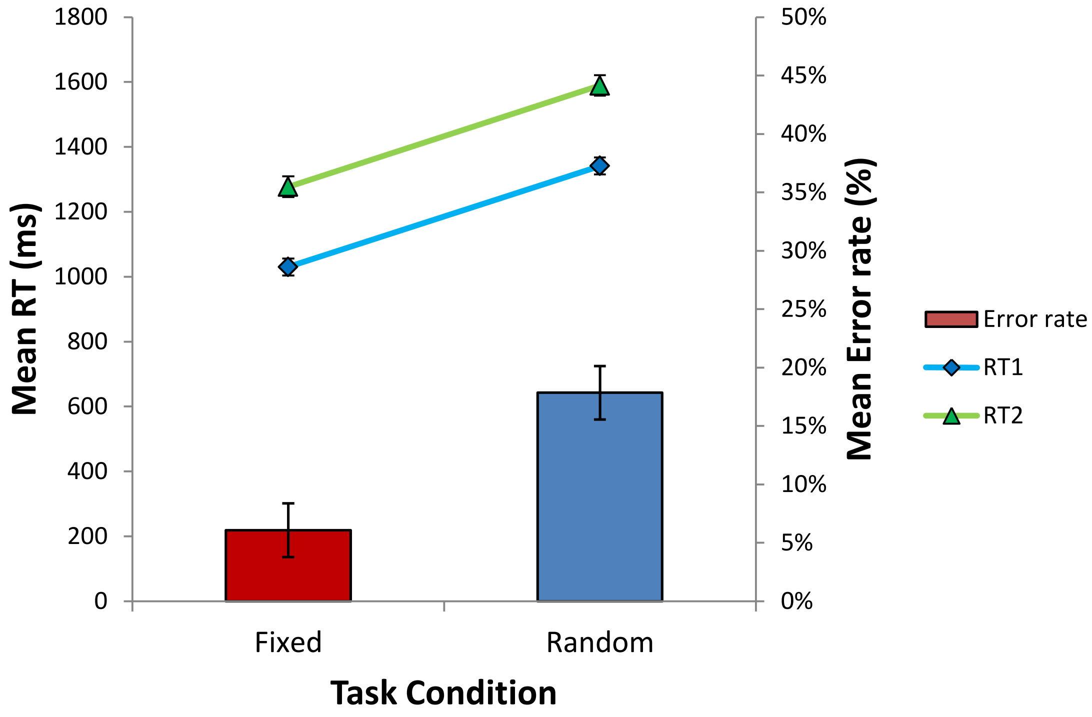


Figure 3.15: Mean response times (left axis, lines) and error rates (right axis, bars) for each dual-task condition of experiment 2c. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

3.4.3 Discussion

In experiment 1, using cognitive subtraction, we showed that recall performance was lower after performing a dual-task during the retention interval as compared with performing a single task. By using a parametric manipulation, we confirmed and extended this finding and showed that performing a difficult dual-task condition led to lower recall performance than an easy dual-task.

The current findings support and extend the conclusions from experiment 1b that processing of PRP dual-tasks is related to WM. Experiment 2c confirmed that this relationship is not simply due to a potentially higher memory demand in the dual-task as compared to the single task due to increased stimulus response mappings in the dual-task. Instead, the relationship seems to arise from common demands on controlled attention. In more detail, the order in which tasks are processed at the bottleneck stage was changed which involves switching and inhibition, both important executive functions needed in the performance of random order dual-tasks (De Jong, 1995; Luria & Meiran, 2003). Changing the order demands the same mental resources as short-term memory maintenance. The TBRS model suggests that this mental resource is controlled attention, i.e. executive functions. Thus, the current study provided further support for the hypothesis that the processes which actively schedule processing at a bottleneck are related to or even identical to the executive functions of WM.

Referring back to the feedback participants received on their performance to maintain their accuracy levels at 80%, which was done to make sure participants did not trade off. In this experiment, error rates were higher in the random condition compared to the fixed condition. However, despite the significant difference in error rates between fixed and random performance, we still found an effect on memory performance. Furthermore, this effect in recall performance may be underestimated due to higher error rates in the random condition. If participants had matched their performance level in the random condition to that in the fixed condition, then memory performance in the random condition would have probably been much worse. Overall, average error rates were not extremely high (<25 %) indicating that participants did focus on their performance in the processing tasks.

3.5 Experiment 2d: Switches (1 to 9)

When looking at the two dual-task conditions in experiment 2c in more detail, it appears that they might not only differ in their demands on task order coordination, but additionally in their demands on cue processing. The cue, which informed participants about the order in which they had to respond to the component tasks (a square or diamond around the circle), was presented only in the random-order condition and not in the fixed order condition. Participants likely kept the cue meanings in their short-term memory so that the random order condition may have imposed higher memory demands, which presents an alternative explanation for the findings of experiment 2c. To rule out this alternative explanation, a further experiment was conducted in which two random conditions were presented, one with a low and one with a high number of switches. In both cases, participants needed to maintain cue meaning and process the cue. It is expected that a condition with a high number of switches should result in poorer memory recall as compared to a condition with a low number of switches.

3.5.1 Method

3.5.1.1 Participants

Eight (5 female) participants (mean age: 28 years, SD = 6.6, range 21-41 years) took part in the study after having given written informed consent. The study was approved by Brunel University's College of Health and Life Sciences Ethics Committee and participants received £8 for their participation. The information leaflet, consent form, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 2.

3.5.1.2 Tasks

The experiment consisted of a WM task with preload procedure consisting of the following phases: memory encoding phase, retention interval processing phase (low or high switches dual-task), recall phase and feedback. This experiment did not use a cue to inform the participant about the upcoming trial because for the participant there was no distinction between conditions. They had to always pay attention to the cue to determine the order in which they had to respond. The phases of experiment 2d were the same as experiment 2c except for the following changes.

Retention interval. This lasted for 30.8 seconds during which participants performed 11 dual-task trials (2800 ms each) with between 1 and 9 (but not 5) switches. The retention interval was prolonged to 11 trials to make 9 switches possible and 5 switches were not used so the number of switches could be divided in two groups (1 to 4 switches being “low number of switches” and 6 to 9 “high number of switches”. Again, only dual-task conditions were used in the main experiment but the single tasks were used during the practice. The cue around the circle indicated the response order and participants had 2300 ms to respond to both stimuli with a total trial duration of 2800 ms (fixation cross and feedback both lasting 250 ms).

Procedure: There was again one memory load and each participant performed 24 memory trials (three of each switch condition (1 till 9, except 5). The main experiment lasted about 25 min and followed approx. 30 min of practice of all tasks (alone and under dual-task conditions). Four different pseudo-randomized memory trial sequences were created an evenly used across participants.

3.5.2 Results

To simplify the analyses, the switch conditions were divided into two groups. The first condition is “Low switches” which contain processing tasks with 1-4 switches and the second condition is “High switches” with 6-9 switches. Since this was a pilot with eight participants, no outlier analysis was performed.

3.5.2.1 Recall performance

To test whether the switch manipulation had an effect on memory recall, the relative recall between the low and high switch dual-task processing task conditions was compared using a paired sample t-test. The relative recall was not significantly different between the low switch (0.46 ± 0.19) and the high switch (0.51 ± 0.19) condition ($t(7) = 1.26$, $p = 0.25$) (Figure 3.16).

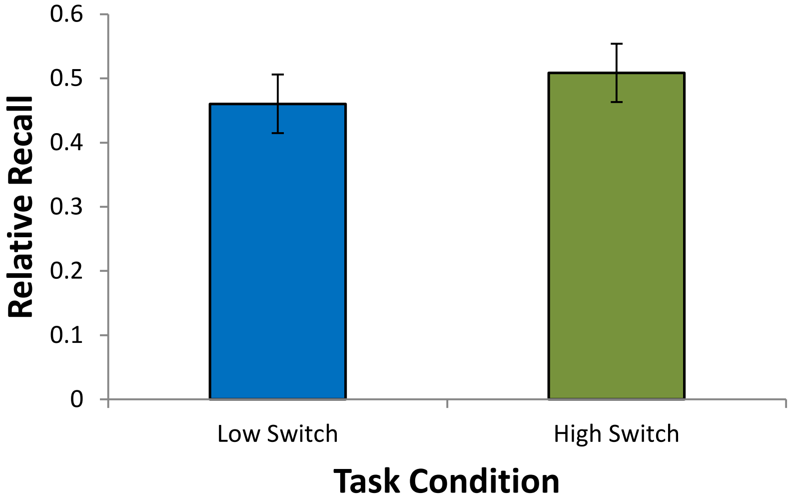


Figure 3.16: Relative recall performance for fixed and random conditions of experiment 2d. Error bars denote 95% confidence intervals (Loftus & Masson, 1994).

The relative recall performance of the different number of switches shows that the relative recall performance only slightly increased for 6 and 7 switches (Table 3.4, Figure 3.17).

Table 3.4: Relative recall performance for the different number of switches of experiment 2d.

Number of switches	Relative recall performance
1	0.42 ± 0.14
2	0.48 ± 0.26
3	0.48 ± 0.29
4	0.46 ± 0.26
6	0.43 ± 0.29
7	0.55 ± 0.19
8	0.60 ± 0.23
9	0.45 ± 0.29

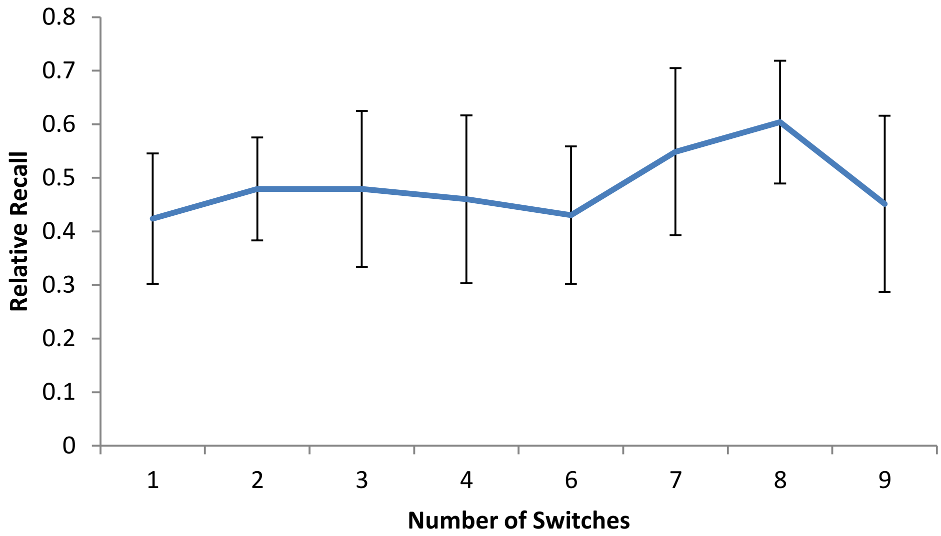


Figure 3.17: Relative recall performance for the different number of switches of experiment 2d. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

3.5.2.2 Processing Task performance.

Performance in the processing tasks which were presented during the retention interval was analysed in terms of response times and error rates.

Response times. A 2x2 repeated-measures ANOVA with factors response (RT1, RT2) and processing task (low and high switches) was conducted to analyse the response times for both switch task conditions (Table 3.5, Figure 3.18). The main effect of response was significant ($F(1, 7) = 48.25$, $p < 0.001$). Follow-up t-tests showed that for both low and high switch task conditions, the RT2s were significantly longer than their respective RT1s (all $t(7) > 6.40$, $p < 0.001$). The main effect of processing task was significant ($F(1, 7) = 80.16$, $p < 0.001$). Follow-up t-tests showed that response times to the first stimulus were significantly faster for the low switch (1252 ± 87 ms) compared to the high switch condition (1340 ± 91 ms) ($t(7) = 9.68$, $p < 0.001$). Also RT2s were significantly faster for the low switch (1535 ± 128 ms) compared to the high switch condition (1649 ± 99 ms) ($t(7) = 7.97$, $p < 0.001$). The interaction between response and processing task was significant ($F(1, 7) = 10.26$, $p < 0.001$ (Table 3.5, Figure 3.18).

Table 3.5: Response times in ms and error rates in percentages of the different task conditions of experiment 2d.

Variable	RT in ms		Error rate in %
Processing Task	RT1	RT2	
Low (1-4) switches	1252 ± 87	1535 ± 128	20.5 ± 11.2
High (6-9) switches	1340 ± 91	1649 ± 99	20.8 ± 10.7

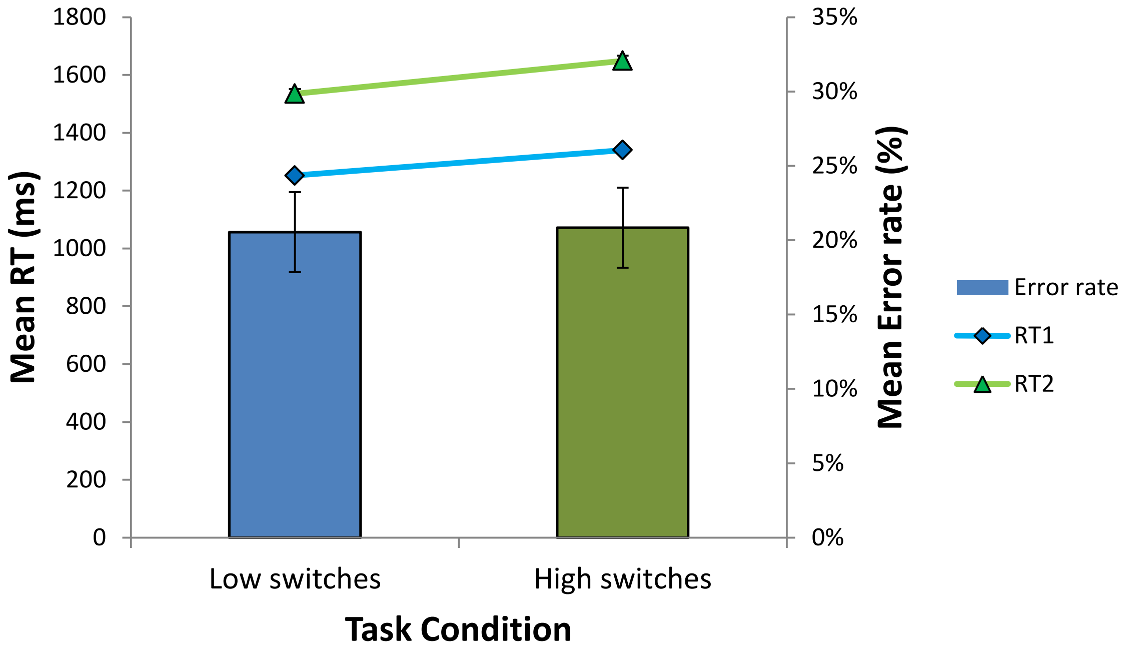


Figure 3.18: Mean response times (left axis, lines) and error rates (right axis, bars) for each dual-task condition of experiment 2d. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

Errors. Error rates between the low switch (20.5 ± 11.2 %) and high switch condition (20.8 ± 10.7 %) did not significantly differ ($t(7) = 0.12$, $p = 0.90$). This meant that participants found the two conditions as being of equal difficulty. Overall, average error rates were not extremely high (<25%) indicating that participants did focus on their performance in the processing tasks (Table 3.5, Figure 3.18).

3.5.3 Discussion

Experiment 2c showed that recall performance was lower after performing a random dual-task as compared to performing a fixed dual-task. Experiment 2d tried to replicate and extend these findings by ruling out possible effects of additional cue processes on recall performance during the random task condition as compared to the fixed condition. New random dual-task conditions were created all having a different number of switches. For the analyses, the conditions were divided into two groups, one with low number of switches (1-4 switches) and one with high number of switches (6-9 switches). Results showed that the recall performance did not significantly differ between low and high switches. In fact, the recall performance in the high switch condition was numerically larger compared with the low switch condition which is against our prediction. This result in recall difference could have been because for participants it was not clear that there were two conditions in the experiment (there was no cue to inform the participant on the number of switches in the upcoming trial). This was confirmed by the post-questionnaire which had an additional question: "Did you recognize that there were two conditions in the experiment?". All participants answered "No" to this question. This was followed up by asking them verbally whether they saw differences in the memory trials, because actually there were eight different switch numbers and participants did not know that the number of switches would be split in two for the analyses. Therefore, the difference between the two conditions was not made explicit enough for participants if it seemed that there was just one condition in the main experiment. To circumvent this, a new experiment was conducted, experiment 2e.

3.6 Experiment 2e: low (2) vs high (9) switches

For participants in experiment 2d it was not clear that there were different conditions in the retention interval. To deal with this, a follow-up experiment was conducted where explicitly two random conditions in the retention interval were created; one with a low (2) number of switches and one with a high (9) number of switches.

3.6.1 Method

3.6.1.1 Participants

Thirty-four (29 female) participants (mean age: 20 years, SD = 5.5, range 18-46 years) took part in the study after having given written informed consent. The study was approved by Brunel University's College of Health and Life Sciences Ethics Committee and participants received course credits for participation. The information leaflet, consent form, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 2.

3.6.1.2 Tasks

The experiment again consisted of a WM task with preload procedure consisting of the following phases: cue, memory encoding phase, retention interval processing phase (low or high switches dual-task), recall phase and feedback. The memory encoding phase, recall phase and feedback were the same as the previous experiment, experiment 2d. This time the cue could be either "Low Switches" or "High Switches" and was displayed for 4 seconds. The retention interval was slightly changed.

<u>Retention Interval Processing Phase.</u> This lasted 35.2 seconds during which participants performed one of the two processing tasks, i.e. random low switches or random high switches. While only dual-task blocks were used in the main experiment, the single tasks were used during the practice before the experiment to familiarize participants with the component tasks. The dual-task conditions were the same as in experiment 2d except for the following changes. Again, the cue was used to indicate the order in which the participant needed to respond to the stimuli, diamond for colour first, square for tone first. Participants had 2700 ms (instead of 2300 ms) to respond to both stimuli, since it

is a difficult task. There were two different order conditions (low and high switches) in the dual-task and each processing task consisted of 11 trials each lasting 3200 ms. In the low switch condition, there were always 2 switches present in the retention interval of 11 trials and in the high switch condition there were 9 switches.

Procedure. There was one memory load (6 letters) only and 2 different types of dual-task. In total, each participant performed 20 memory trials (10 per dual-task condition). The main experiment lasted about 20 min. Before this, participants practiced all tasks (including the single tasks) for approx. 30 min, which included a thorough practice of the random dual-tasks.

3.6.2 Results

Again, the impact of dual-task performance on WM was analysed by the recall performance in the memory task. One participant was classified as an outlier (mean difference in recall between the low and high switch condition was more than 3 standard deviation below the group mean difference) and hence excluded from the analysis.

3.6.2.1 Recall performance

To test whether the switch manipulation affected memory recall, the relative recall between the low and high switch processing task conditions was compared using paired-sample t-tests. The relative recall was significantly higher in the low switches (0.57 ± 0.21) as compared to the high switches condition (0.54 ± 0.19) ($t(32) = 2.11$, $p = 0.04$) (Figure 3.19). This supports the hypothesis that the difficulty of a dual-task adversely affects memory performance.

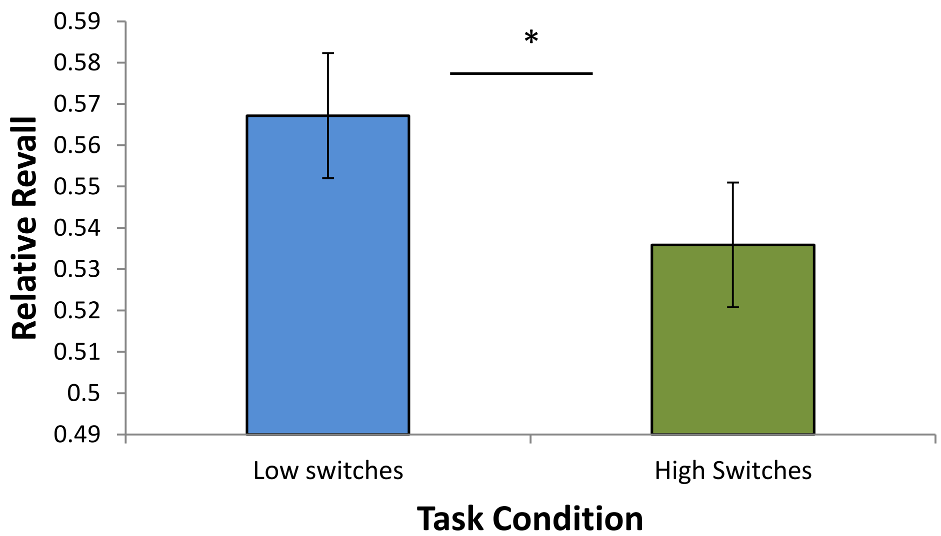


Figure 3.19: Relative recall performance for low and high switches dual-task conditions of experiment 2e. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**. Results of paired samples t-tests testing for recall performance differences are shown (*p < 0.05).**

3.6.2.2 Processing Task performance

The performance of the dual-tasks was again measured by response times and error rates.

Response times. A 2x2 repeated measures ANOVA with factors response (RT1, RT2) and processing task (low and high switches) was conducted to analyse the response time for both switch task conditions (Table 3.6, Figure 3.20). The main effect of response was significant ($F(1, 32) = 214.44$, $p < 0.001$). Follow-up t-tests showed that for both switch task conditions, the RT2s were significantly longer than their respective RT1s (all $t(32) > 15.31$, all $p < 0.001$). The main effect of processing task was significant ($F(1, 32) = 60.57$ $p < 0.001$). Follow-up t-tests showed that both the RT1s (1452 ± 171 ms) and RT2s (1736 ± 217 ms) of the high switch condition were significantly longer than the RT1s (1320 ± 138 ms) and the RT2s (1610 ± 176 ms) of the low switch condition respectively (all $t(32) > 7.45$, all $p < 0.001$). There was no interaction effect between response and processing task ($F(1, 32) = 0.93$, $p = 0.34$).

Table 3.6: Response times in ms and error rates in percentages of the different task conditions of Experiment 2e.

Variable	**RT in ms**		**Error rate in %**
Processing Task	RT1	RT2	
Low switch	1320 ± 138	1610 ± 176	20.68 ± 14.08
High switch	1452 ± 171	1736 ± 217	28.51 ± 18.54

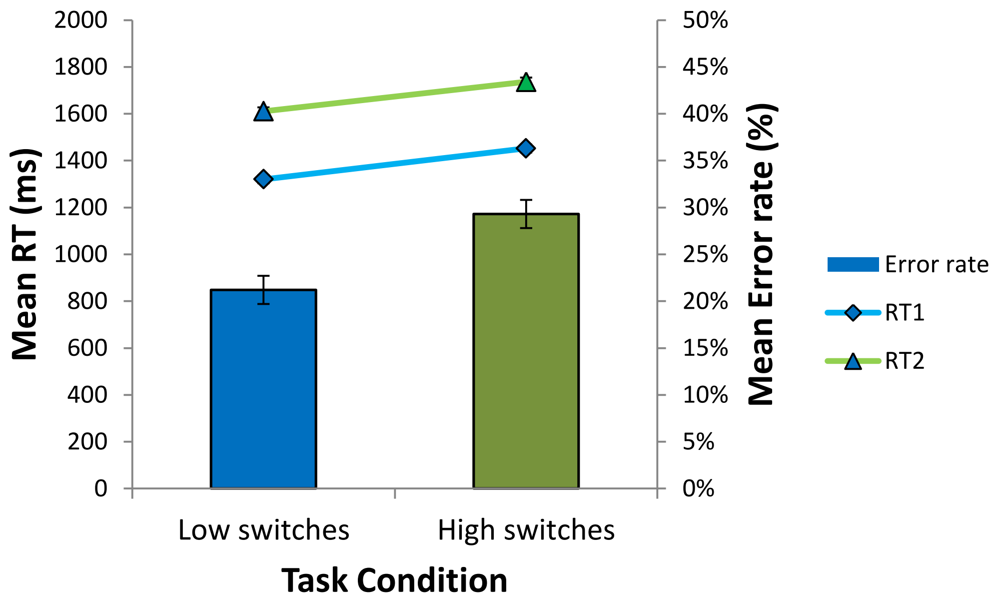


Figure 3.20: Mean response times (left axis, lines) and error rates (right axis, bars) for each dual-task condition of experiment 2e. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

Errors. Participants made significantly more errors in the high switch condition (28.51 ± 18.54 %) compared to the low switch condition (20.68 ± 14.08 %) ($t(32) = 5.32$, $p < 0.001$) (Table 3.6, Figure 3.20).

3.6.3 Discussion

Experiment 2c showed that recall performance was lower after performing a random dual-task during the retention interval as compared to performing a fixed dual-task. Experiment 2e replicated and refined these findings by showing that memory performance is worse when participants perform a high number (9) of switches during the retention interval as compared to a low number (2) of switches when the cue at the beginning of the memory trials informs the participant about the type of switches.

Experiment 2e ruled out the alternative explanation that a difference in memory load might account for the observed differences between fixed and random order conditions. Such differences were absent in the current experiment, because both conditions required the processing of the cue. Based on the TBRS model we suggest that instead both tasks, PRP dual-tasks with active scheduling of bottleneck processing and memory maintenance, demand controlled attention, i.e. executive functions. Consequently, we conclude that PRP dual-tasks do demand the executive functions of WM beyond the demands imposed by the sole performance of the single-tasks.

3.7 Experiment 2f (replication)

In this chapter several experiments were described to fine-tune the experimental design. For instance, the study with the square (4 boxes) (experiment 2a) was initially changed because participants found it too confusing. This led to the development of the cue around the circle, either a diamond or a square, to indicate the order in which the participant had to respond. To confirm previous results, another experiment was conducted, i.e. a replication experiment. A power analysis was used to calculate the required sample size. This was based on the first experiment (experiment 1b) where recall performance of the single tasks was compared to that of the dual-task and showed the required number of participants to be 33.

3.7.1 Method

3.7.1.1 Participants

Thirty-three (30 female) participants (mean age: 20 years, SD = 1.4, range 18-23 years) took part in the study after having given written informed consent. The study was approved by Brunel University's College of Health and Life Sciences Ethics Committee and participants received course credits for participation. The information leaflet, consent form, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 3.

3.7.1.2 Tasks

The experiment again consisted of a WM task with preload procedure consisting of the following phases: cue, memory encoding phase, retention interval processing phase (low or high switches dual-task), recall phase and feedback. Since this was a replication experiment, all phases were identical to experiment 2e as described in 3.6.1.2.

3.7.2 Results

Again, the impact of dual-task performance on WM was analysed by the recall performance in the memory task. No participant was excluded.

3.7.2.1 Recall performance

To test whether the switch manipulation affected memory recall, the relative recall between the low and high switch processing task conditions was compared using paired-sample t-tests. The relative recall was only numerically but not significantly higher in the low switches (0.55 ± 0.22) as compared to the high switches condition (0.53 ± 0.25) ($t(32) = 0.92$ $p = 0.37$) (Figure 3.21).

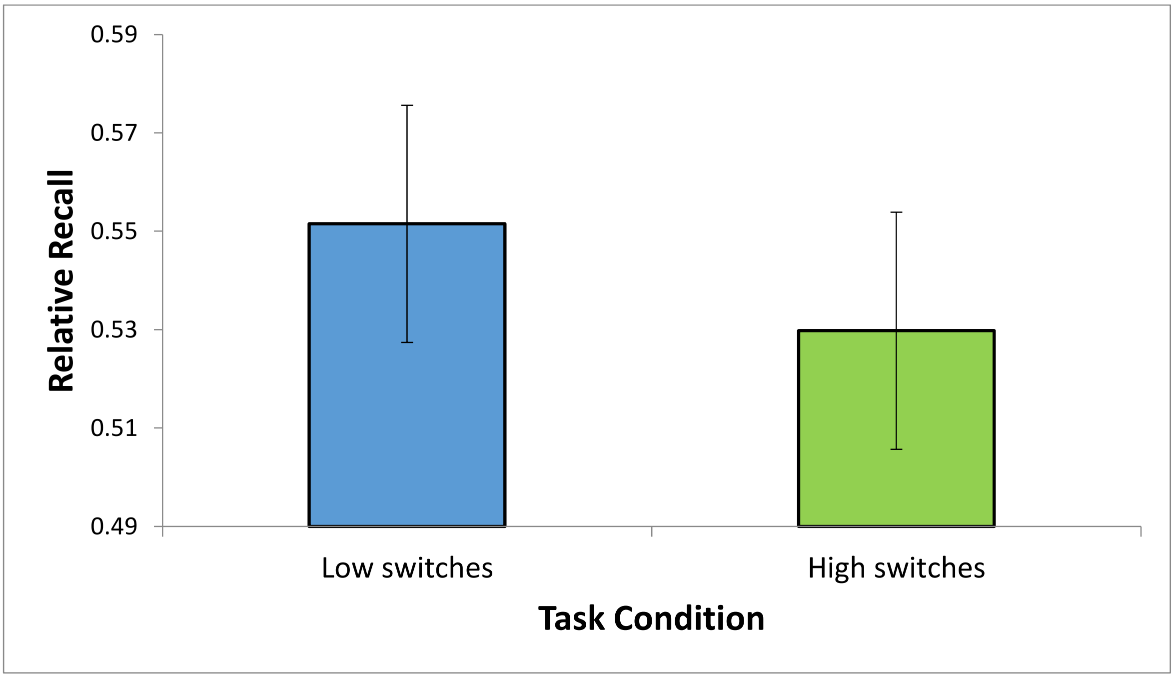


Figure 3.21: Relative recall performance for low and high switches dual-task conditions of experiment 2f. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**. Results of paired samples t-tests testing for recall performance differences are shown (not significant).**

3.7.2.2 Processing Task performance

The performance of the dual-tasks was again measured by response times and error rates.

Response times. A 2x2 repeated measures ANOVA with factors response (RT1, RT2) and processing task (low and high switches) was conducted to analyse the response time for both switch task conditions (Table 3.7, Figure 3.22). The main effect of response was significant ($F(1, 32) = 302.60$, $p < 0.001$). Follow-up t-tests showed that for both switch task conditions, the RT2s were significantly longer than their respective RT1s (all $t(32) > 16.73$, all $p < 0.001$). The main effect of processing task was significant ($F(1, 32) = 80.09$ $p < 0.001$). Follow-up t-tests showed that both the RT1s (1500 ± 172 ms) and RT2s (1782 ± 197 ms) of the high switch condition were significantly longer than the RT1s (1380 ± 153 ms) and the RT2s (1666 ± 175 ms) of the low switch condition respectively (all $t(32) > 8.54$, all $p < 0.001$). There was no interaction effect between response and processing task ($F(1, 32) = 0.77$, $p = 0.39$).

Table 3.7: Response times in ms and error rates in percentages of the different task conditions of Experiment 2e.

Variable	RT in ms		Error rate in %
Processing Task	RT1	RT2	
Low switch	1380 ± 153	1666 ± 175	16.45 ± 7.53
High switch	1500 ± 172	1782 ± 197	22.53 ± 9.27

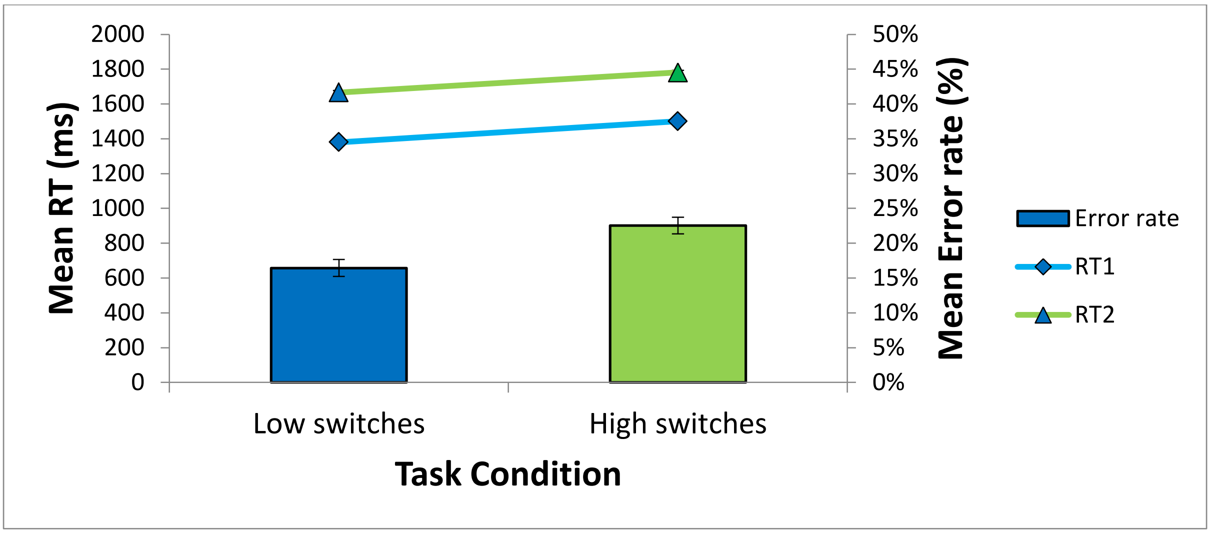


Figure 3.22: Mean response times (left axis, lines) and error rates (right axis, bars) for each dual-task condition of experiment 2e. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

Errors. Participants made significantly more errors in the high switch condition (22.53 ± 9.27 %) compared to the low switch condition (16.45 ± 7.53 %) ($t(32) = 5.14$, $p < 0.001$) (Table 3.7, Figure 3.22).

3.7.3 Discussion

Experiment 2e showed that memory performance is worse when participants perform a high number (9) of switches during the retention interval as compared to a low number (2) of switches when the cue at the beginning of the memory trials informs the participant about the type of switches. Experiment 2f was a replication experiment and the results showed the expected difference between the recall performance in low switches compared to high switches. However, this difference was only numerical and not statistically different[1] and therefore the results of experiment 2e were not replicated. Based on the previous experiments and the literature it is more likely to find an effect between the two switch conditions than not. Perhaps other factors interfere with what typically happens and the expected effect is masked by this. An indication for this could be a certain need in difference in response times between the two conditions. This difference was quite large in previous experiments, (experiment 1b: (DT RT1 - ST RT1) 287 ms, experiment 2c: RT2 (Random – Fixed) 312 ms), which also led to a significant difference in recall performance. However, for the two experiments on switches these difference in response times were rather small (experiment 2e: RT2 (High – Low Switches) 126 ms and for experiment 2f: 116 ms). This could indicate that a larger response time difference between conditions is needed to better distinguish between those and makes it more likely to find significant differences in recall performance.

Future research is needed to fine tune the paradigm and to investigate potential other effects that could be interfering. Such factors could be task difficulty, information overload due to the difficulty of the task, the way the participants process the stimuli, optimal trial duration (potentially even adjust this per subject). Information overload due to the difficulty of the task could interfere with recall performance, because the overload of information could prevent the work of the rehearsal mechanism and therefore this is something that could be looked into. Also, large response time differences between the different conditions might be needed to see differences in recall performances between the conditions. This could be achieved by determining the optimal trial duration adjusted per subject, since there is a range of response times for the processing task across subjects.

An overview of all the different order experiments is given in Table 3.8.

[1] Even two experts in the field (Klaus Oberauer and Baptist Liefooghe) have no explanation for this finding. They also expect a difference in recall between low and high switches given the other behavioural findings.

Table 3.8: Overview of the parameters used in the different order experiments

	N	Duration of cue	#trials in retention interval	Duration of 1 trial in retention interval	Conditions used in the retention interval	Indication of response order	p-value for recall performance between conditions	RT2 difference between conditions	Result
2a	8	3 sec	6	2300 ms	Fixed 1: TC Fixed 2: CT Random 1: aabbaa Random 1: bbaabb Random 2: ababab Random 2: bababa	Frame	F-RL: p = 0.58 F-RH: p = 0.59 RL-RH: p = 0.68	F-RL: 51 ms F-RH: 132 ms RL-RH: 80 ms	Moving of the visual stimulus in the frame to indicate the order was too difficult for participants.
2b	21	3 sec	6	2300 ms	Fixed 1: TC Fixed 2: CT Random 1: aabbaa Random 1: bbaabb Random 2: ababab Random 2: bababa	Square, Diamond	F-RL: p = 0.84 F-RH: p = 0.95 RL-RH: p = 0.78	F-RL: 134 ms F-H: 170 ms RL-RH: 36 ms	No significant difference between fixed and random, participants found it difficult to perform the processing tasks in the retention interval.
2c	17	4 sec	5	2300 ms	Fixed 1: TC Fixed 2: CT Random: 6 different ones, with at least 2 switches	Square, Diamond; Always in pairs	F-R: p = < 0.01	F-R: 312 ms	Recall performance significantly higher in fixed compared to random processing task condition.
2d	8	No cue	11	2300 ms	Random Low: 0-4 switches Random High:6-10 switches	Square, Diamond	RL-RH: p = 0.25	RL-RH: 114 ms	Recall performance not significantly different between random low and high. Participants did not recognize the different switches.
2e	34	4 sec	11	2700 ms	Random Low: 2 switches Random High: 9 switches	Square, Diamond	RL-RH: p = 0.04	RL-RH: 126 ms	Recall performance significantly lower in random high compared to random low condition.
2f	33	4 sec	11	2700 ms	Random Low: 2 switches Random High: 9 switches	Square, Diamond	RL-RH: p = 0.37	RL-RH: 116 ms	Recall performance only numerically lower in random high compared to random low condition.

Chapter 4 : The effect of SOA in the PRP dual-task on recall performance

4.1 Introduction

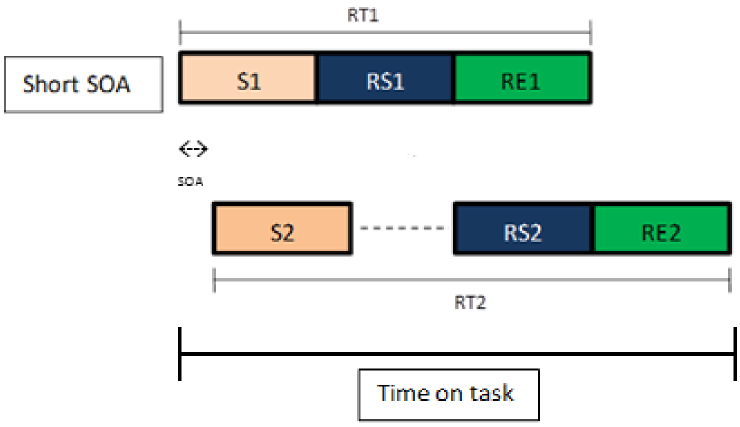
Experiments 1 and 2 showed that PRP dual-tasks demand the executive functions of WM. The next experiment aimed at corroborating this conclusion further by using a different parametric manipulation approach. In more detail, the time between the onset of the stimulus of the first task (S1) and the onset of the stimulus of the second task (S2), known as the stimulus onset asynchrony (SOA), was manipulated. This is probably the most widely used manipulated parameter in the PRP paradigm (Pashler, 1994). The TBRS model was again used to predict the effect of an SOA manipulation on memory performance. These predictions are sometimes counterintuitive and, therefore, will be discussed in detail further below.

Except for minor changes, experiment 3 used the same design and stimuli as experiment 1b, i.e. a complex WM span task with preload procedure and variations in the nature of the processing task performed during the retention interval. The processing tasks were dual-tasks with either a short or long SOA.

The theoretical basis of the experiment is the proposal that shorter SOAs lead to higher demands on executive functions that schedule task processing at the bottleneck than longer SOAs (Jiang, 2004; Logan & Gordon, 2001; Meyer & Kieras, 1997; Szameitat, Schubert, & Müller, 2011). This is because at short SOAs both tasks arrive at the bottleneck mechanism closely in time and directly compete for processing. Hence, executive functions, such as inhibition and monitoring, are more highly required in this situation to avoid processing errors (e.g. starting to process the second task first). These demands on executive functions gradually decrease with increasing SOA, because the increased temporal separation between stimuli leads to less competition for processing. At very long SOAs the response to the first stimulus is given before the second stimulus is even presented, and then executive functions scheduling the processing of the tasks at the bottleneck are absent (Jiang et al., 2004). The TBRS model predicts that higher demands on executive functions impair memory performance more than lower demands, and so it predicts that memory performance should *decrease* with decreasing SOA.

However, when analysing the task processes in more detail, the TBRS model might also predict a different pattern. Crucially, the TBRS concept of controlled attention does not only incorporate the classic executive functions as demanded in the PRP task, such as inhibition, switching and monitoring, but also attention in a more general sense. Thus, several other task processes, for instance related to perception or motor execution, may also occupy controlled attention. For instance, Liefooghe et al. (2008) showed that in a task-switching paradigm a perceptual difficulty manipulation (degrading of stimuli) can have the same effect on memory performance as an executive function manipulation (task switching).

Assuming both task processes demand controlled attention the question arises how the demands a task places on controlled attention can be estimated. The current study uses a parameter termed time on task (ToT), which quantifies the time a participant is occupied with the task. For single tasks, this is simply the response time. However, in dual-task situations, this is slightly more complex to calculate. If the SOA is short, then the second stimulus is presented before the participant has responded to the first stimulus, i.e. the processing of the two tasks overlaps in time. In that case, ToT is the time between the first stimulus (of task 1) and the second response (of task 2). When the SOA is long, then participants may respond to the first task before the second stimulus is presented. In these cases, when RT1 is smaller than the SOA, ToT is the sum of the response times of task 1 (RT1) and task 2 (RT2) as is displayed in Figure 4.1. Thus, if ToT does indeed quantify the demands on controlled attention, then the TBRS model predicts that memory performance should *increase* with decreasing SOA.



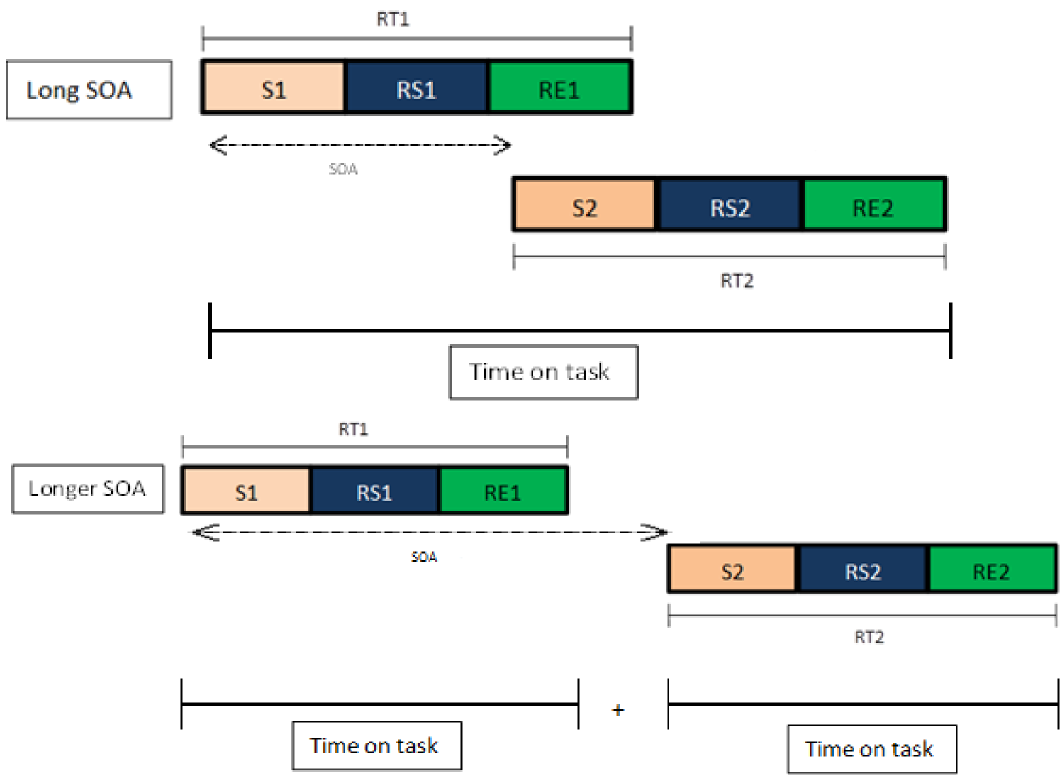


Figure 4.1: Predictions of the PRP paradigm on the time on task for short and long SOA. Visual representation of how ToT increases with increasing SOA.

Therefore, demands on executive functions (increase with decreasing SOA) and ToT (decrease with decreasing SOA) result in completely opposite predictions for the effect of SOA on memory performance (Figure 4.2). As a third possibility, it is conceivable that both effects exist and affect performance in opposing directions. If both of these effects have approximately the same size, they would cancel each other out, and the TBRS model would predict that memory performance is independent of the SOA ("Mix" in Figure 4.2).

Taken together, the PRP-executive functions and ToT theories result in completely opposite predictions. As discussed above, they are independent aspects which independently demand controlled attention and hence independently affect memory performance (Figure 4.2).

- If it is ToT only, i.e. if it is about any form of attention, then the following prediction can be made. The ToT increases with SOA and hence demands in controlled attention increase with increasing SOA. Hence, recall performance decreases with increasing SOA (blue line in Figure 4.2).

- If it is purely about executive functions, then one would predict the opposite pattern. Short SOAs demand executive functions stronger and hence controlled attention is demanded longer which leads to a reduction in recall performance. At long SOAs, executive functions are demanded to a lesser extent due to less interference. Here, the prediction is that recall performance will increase with increasing SOA (red line in Figure 4.2).

- In case both are true, then one would expect a mixture of both effects, i.e. results will be any gradual form between ToT and executive function demands. In case ToT and executive functions have roughly the same effect size, then memory recall should be largely independent of SOA (green line in Figure 4.2).

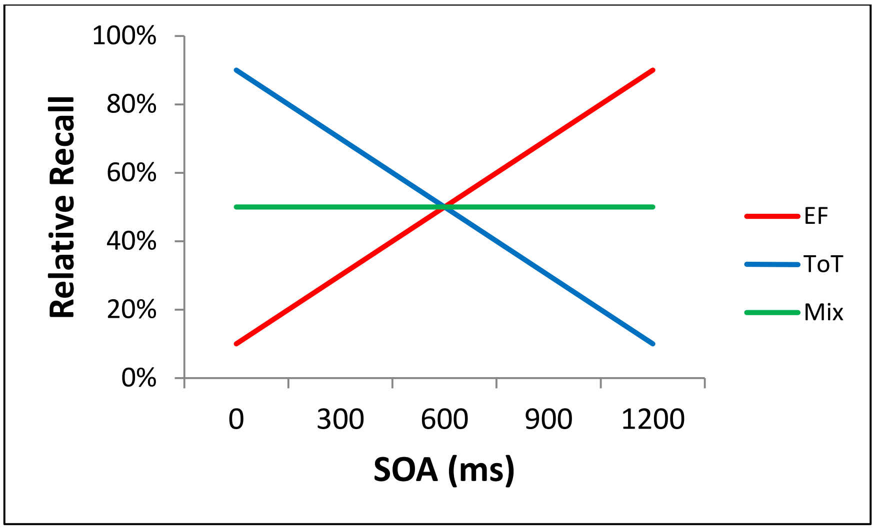


Figure 4.2: Predicted relationship between SOA and relative recall performance for the different theories. Note, EF = executive functions and ToT = time on task.

4.2 Experiment 3: SOA manipulation

4.2.1 Method

4.2.1.1 Participants

Twenty-five (10 female) participants (mean age: 27 years, SD = 3.1, range 23-35 years) took part in the study after having given written informed consent. The study was approved by Brunel University's College of Health and Life Sciences Ethics Committee and participants received £8 for participation. The information leaflet, consent form, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 3.

4.2.1.2 Tasks

The experiment again consisted of a WM span task with preload procedure with the following phases: cue, memory encoding phase, retention interval processing phase (5 different SOA dual-tasks), recall phase and feedback. The phases of experiment 3 were the same as experiment 1b except for the following changes.

Cue. The cue instructed the participants about the SOA condition (0 ms, 300 ms, 600 ms, 900 ms or 1200 ms) of dual-task was shown for 3 seconds. Participants were familiarized with all SOA conditions during practice.

Retention Interval Processing Phase. The retention interval lasted 14 seconds during which participants performed one of the five SOA processing task. While only dual-task blocks were used in the main experiment, the single tasks were used during the practice before the experiment to familiarize participants with the component tasks.

Feedback. Participants received feedback at the end of each memory trial about their performance in the processing task, similar to experiment 1b. For all SOA conditions, the same cut-off value was used which was determined from the SOA 0 ms condition in the practice.

Processing tasks.

Auditory and Visual Single Task. The procedure for these tasks was the same as experiment 1 except that participants had 2300 ms to respond instead of 2000 ms.

Dual-Task. The dual-task condition was the same as in experiment 1, except that five different SOAs (0, 300, 600, 900 and 1200 ms) were employed across processing task blocks. Irrespective of the SOA, participants had 2300 ms from onset of the first stimulus to respond to both stimuli. Again a trial started with a fixation cross displayed for 250 ms and participants received feedback on each trial for 250 ms. Participants responded in the same fixed order, i.e. first to the auditory stimulus and then to the visual stimulus, as in experiment 1b. All processing tasks consisted of five trials lasting 2800 ms each.

Procedure. There was one memory load (6 letters) only and five different SOA dual-tasks. Each participant performed 45 memory trials (9 per SOA condition) and the main experiment lasted about 30 min. Before this, participants practiced all tasks (including the single tasks) for approx. 15 min.

4.2.2 Results and Discussion

The impact of dual-task performance on WM was again analysed by the recall performance in the memory task. No participant was excluded.

4.2.2.1 Recall performance

As previously mentioned, there are three possibilities on how the SOA may affect memory recall. Firstly, if it is primarily affected by any form of attention and that the demands on controlled attention are estimated by the ToT, then short SOAs (i.e. short ToT) would lead to higher recall performance than long SOAs (long ToT). Secondly, if the demands on controlled attention are mostly determined by the executive functions scheduling task processing, the opposite pattern is expected, i.e. short SOAs (high executive functions demand) would lead to lower recall performance than long SOA (low executive functions demand). Thirdly, the demands on controlled attention may be determined by both of the above. In that case, the effects might cancel each other out, and short and long SOAs would show the same recall performance.

Initial data analyses revealed slightly more variability across the SOAs than expected, which might indicate that nine memory trials per SOA condition are insufficient for a stable estimate of the mean. Therefore, we started our analysis by pooling short and long SOAs (a full analysis showing all SOAs can be found further below). We pooled the SOAs 100 ms and 300 ms into a short SOA condition, because here a bottleneck was present in every trial (RT1 was never shorter than the SOA). On the other hand, we pooled the SOAs 900ms and 1200ms into a long SOA condition, because here a bottleneck was absent in virtually all of the trials (RT1 was shorter than the SOA in most of the trials). For this initial analysis, we left out the SOA 600 ms condition, because this was a mixture of trials with and without a bottleneck present. This pooling resulted in an average of 18 memory trials per SOA condition (short vs long).

Results were in clear support of the last hypothesis, i.e. both effects are present and potentially cancel each other out: short and long SOA conditions showed numerically virtually identical recall performance (short SOA 0.6095 vs long SOA 0.6065). This difference was not statistically significant ($t(24) = 0.17$, $p = 0.87$) (Figure 4.3). Therefore, recall performance may be determined by both, general demands on attention (as assessed by ToT) and specific demands on executive functions (as predicted by models of bottleneck processing).

A potential criticism of this conclusion is that it is based on the interpretation of a null-effect. However, there are a number arguments that suggest this conclusion is valid (cf. (Cortina & Folger, 1998)). First, the observed numerical values were virtually identical and the difference was not significant ($p = 0.87$). In the other experiments we have shown that with twenty (experiment 1b), seventeen (experiment 2c) and thirty-four (experiment 2e) participants there was an effect on memory recall and we did not have that effect here with twenty-five participants. Within this experiment however we were able to show effects, for instance the effect of ToT between the different conditions as is described below, which shows that we have enough power (Cortina & Folger, 1998), although we did not find an effect of SOA on recall performance. Second, a common argument is that the study is too under-powered to show an effect. However, experiments 1 and 2 have shown that with this experimental procedure it is possible to detect effects on recall performance. These two arguments make it appear unlikely that our experimental procedure lacks power per se, and that simply increasing the sample size would reveal a significant difference in recall performance between the SOA conditions. However, the third argument is probably the most important one. It was predicted that ToT is a relevant variable, an assumption supported by previous findings (e.g. Liefooghe et al. (2008)).

Therefore, the effect of ToT was investigated in more detail. This was done by analysing the ToT differences between the short and long SOA conditions. Results showed that in the short SOA condition ToT (1127 ± 160 ms) was significantly shorter than in the long SOA condition (1235 ± 176 ms) ($t(24) = 7.86$, $p < 0.001$) (Figure 4.3). We take this as evidence that indeed the demands on executive functions vary as predicted by the active scheduling account (i.e. high demands in shorter SOAs), that these executive functions demand the controlled attention of WM, and finally, that these effects countered the effects of more general task-related demands on controlled attention.

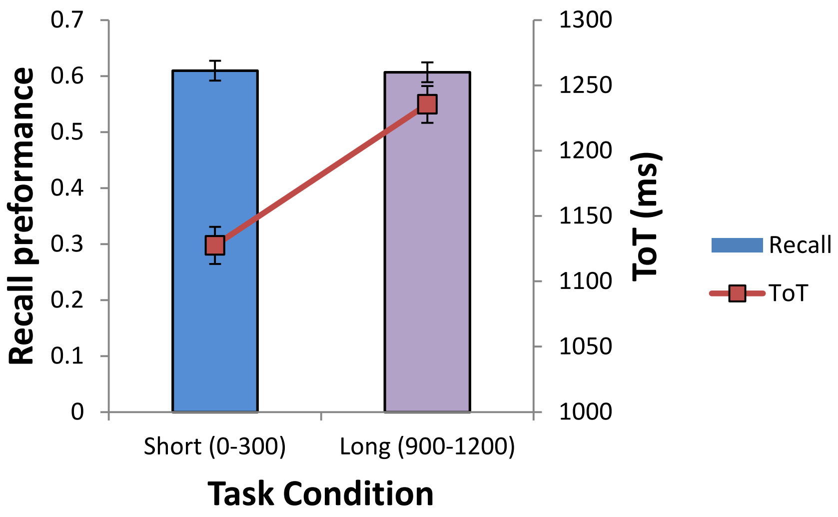


Figure 4.3: Mean recall performance (left axis, bars) and ToT (right axis, lines) for short (0-300 ms) and long SOA (900-1200 ms) of experiment 3. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

For the analyses so far, we have averaged the short (0 ms and 300 ms) and long (900 ms and 1200 ms) SOA conditions. In the following we present the data for all five SOAs (Table 4.1, Figure 4.4). Whilst there was slightly more variability in the data, the same overall pattern was observed, i.e. with decreasing SOA the ToT decreases (one-way repeated measures ANOVA with SOA as independent and ToT as dependent variable $F(4, 96) = 24.18$, $p < 0.001$) while recall performance is largely unaffected by SOA (one-way repeated measures ANOVA with SOA as independent and relative recall performance as dependent variable. Mauchly's test indicated that the assumption of sphericity had been violated for the effect of SOA on recall performance ($\chi^2(2) = 19.02$, $p = 0.025$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ϵ =

0.77), (F(3.07, 73.63) = 0.71, p = 0.56)). The above analyses showed that ToT is highly significant across several SOAs, whilst recall performance between different SOAs is not. These effects seem to be counteracting.

Table 4.1: Relative recall performance and Time on Task of experiment 3 as a function of SOA.

Processing Task	Executive demands	ToT (ms)	Relative Recall
SOA 0	Very high	1121 ± 167	0.614 ± 0.233
SOA 300	High	1134 ± 161	0.605 ± 0.212
SOA 600	Average	1204 ± 153	0.611 ± 0.213
SOA 900	Low	1232 ± 182	0.629 ± 0.253
SOA 1200	Very low	1239 ± 176	0.584 ± 0.216

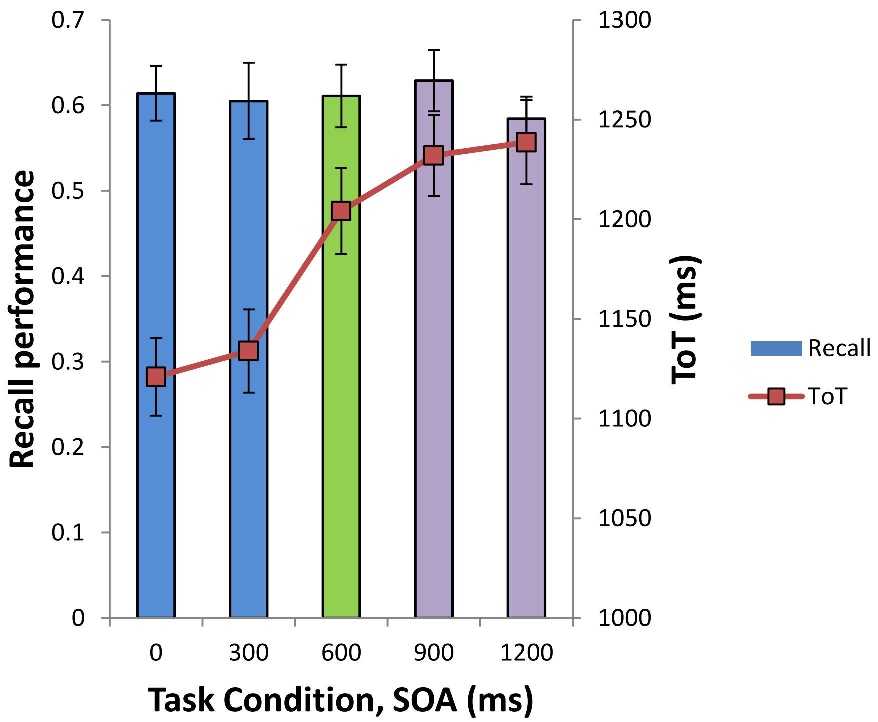


Figure 4.4: Mean recall performance (left axis, bars) and ToT (right axis, lines) for the different SOA conditions of experiment 3. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

Additionally, a regression analysis was performed. For this, the effect ToT (predictor) has on recall performance (predicted) was investigated by a multiple regression analysis. Both the SOA and the ToT value per trial were entered as independent variables whilst the recall performance per trial was the dependent variable. The analysis was based on memory trials of the short and long SOAs, i.e. 36 memory trials per participant across all 25 participants. We derived an estimate of the ToT of a given memory trial by calculating the mean ToT of the five dual-task trials performed during the respective retention interval. Also, each memory trial had an SOA value (short or long) attached to it as well as the relative recall performance. To take into account the difference between within-subject effects and between-subject effects, the regression analysis was performed per subject and one sample t-tests were performed on the standardized beta values produced for each of the independent variables given for each subject. Confirming our initial findings, SOA had no significant influence on memory performance ($t(24) = 0.29$, $p = 0.77$. However, ToT nearly reached significance in predicting memory performance ($t(24) = 1.60$, $p = 0.06$, one-tailed). This suggests that it is only the time the central stages occupy the bottleneck that interferes with maintenance of items in memory.

4.2.2.2 Processing Task performance

The performance of the dual-tasks was measured by response times and error rates. This analysis focused on the existence of the PRP effect.

Response times. To provide evidence that a processing bottleneck has been present in the dual-task, the PRP effect (slowing of RT2 with decreasing SOA with a largely constant RT1) was tested. A 2x5 repeated-measures ANOVA with the factors response (RT1, RT2) and SOA (0, 300, 600, 900, and 1200 ms) revealed the typical PRP effect (Figure 4.5). The main effect of response was significant ($F(1, 24) = 46.67$, $p < 0.001$). Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for both the main effect of SOA ($\chi^2(9) = 21.95$, $p = 0.009$) and for the interaction effect between response time and SOA ($\chi^2(9) = 55.09$, $p < 0.001$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.71$ and $\epsilon = 0.42$ respectively). The main effect of SOA was significant ($F(2.81, 67.67) = 232.93$, $p < 0.001$). Also, response time and SOA showed an interaction effect ($F(1.67, 40.14) = 308.93$, $p < 0.001$).

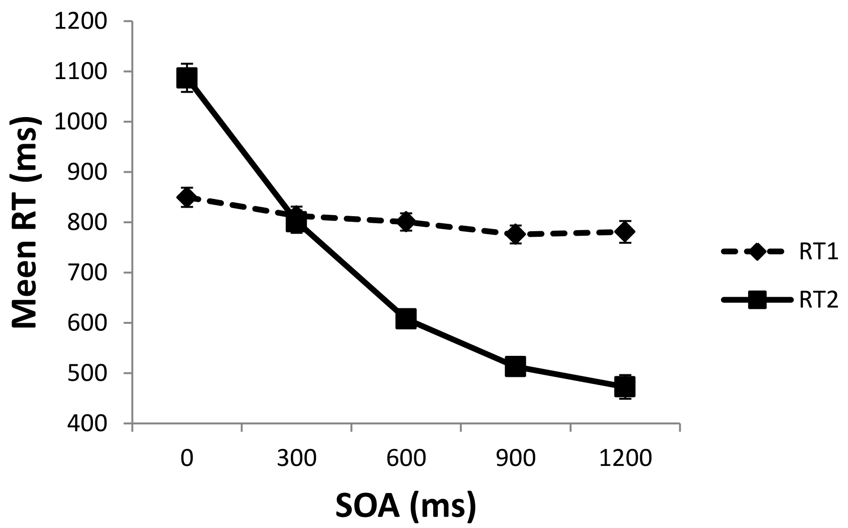


Figure 4.5: Response time data for experiment 3. RT2 (solid line) increases with decreasing SOA whilst RT1 (dotted line) remains roughly constant, indicating the presence of a PRP effect. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

To understand the interaction, follow-up one way repeated-measures ANOVAs were conducted on both response times separately (Figure 4.6). Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for the effect of SOA on RT2 ($\chi^2(9) = 38.28$, $p < 0.001$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.56$). Results showed that the RTs on the second task (RT2) strongly and significantly differed with SOA $F(2.22, 53.38) = 442.77$, $p < 0.001$. Follow-up paired t-tests showed that RT2 significantly increased with decreasing SOA for all subsequent pairs of SOA values (all $t(24) > 4.66$, $p < 0.001$). This means that RT2s of each condition were significantly different from any other condition, with RT2 largest for SOA 0 ms and decreasing with increasing SOA given the smallest RT2 value for SOA 1200 ms. Mauchly's test of sphericity indicated that the assumption of sphericity had also been violated for the effect of SOA on RT1 ($\chi^2(9) = 23.52$, $p = 0.005$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.68$). The RTs on the first task (RT1) significantly differed with SOA ($F(2.72, 65.21) = 8.12$, $p < 0.001$), although not so strongly as RT2. Follow-up paired t-tests for RT1 showed only a significant difference between SOA 0 ms (849 ± 147 ms) and SOA 300 ms (812 ± 142 ms) and between SOA 600 ms (800 ± 151 ms) and SOA 900 ms (775 ± 140 ms) (both $t(24) > 2.34$, $p < 0.03$). An overview of the response times and error rates per SOA is given in Table 4.2 and Figure 4.6.

Taken together, these findings show that a bottleneck has been present during the processing of the PRP dual-task (Pashler, 1994) which was a pre-requisite of the current study.

Table 4.2: Response times in ms and errors in percentage of the different SOA processing tasks of experiment 3.

Variable	**RT in ms**		**Errors in %**
Processing Task	RT1	RT2	
SOA 0 ms	849 ± 148	1087 ± 163	8.18 ± 5.94
SOA 300 ms	812 ± 142	801 ± 150	6.22 ± 4.63
SOA 600 ms	801 ± 152	608 ± 121	7.91 ± 7.09
SOA 900 ms	776 ± 140	513 ± 98	5.87 ± 4.71
SOA 1200 ms	781 ± 135	473 ± 78	6.40 ± 4.77

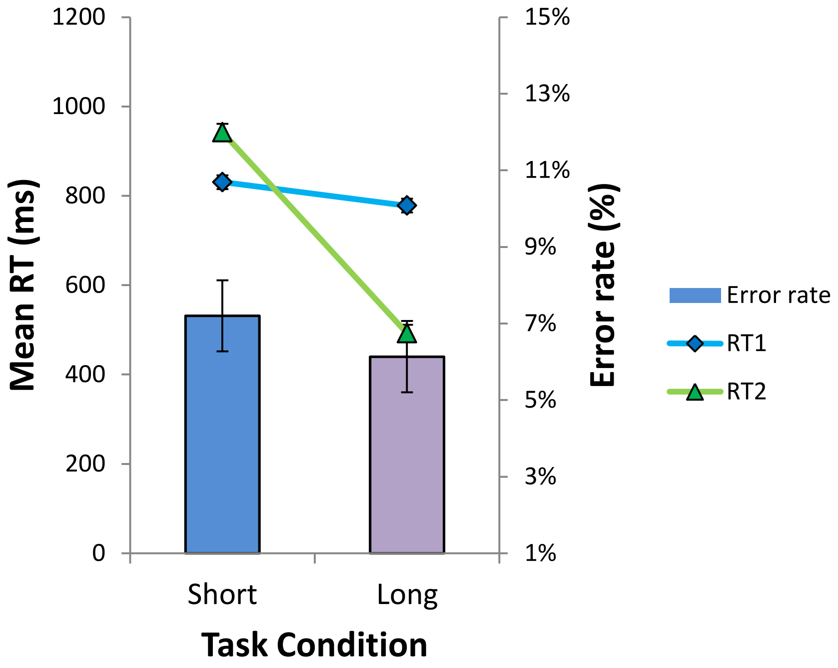


Figure 4.6: Mean response times (left axis, lines) and error rates (right axis, bars) for each the short and long SOA conditions of experiment 3. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

Errors. A one-way repeated-measures ANOVA of error rates and SOA values was conducted to test the error rates between the different SOA values (Table 4.2, Figure 4.6). Mauchly's test indicated that the assumption of sphericity had not been violated. Results showed that error rates did not significantly differ between SOA conditions ($F(4, 96) = 2.00$, $p = 0.10$). Comparing all SOA conditions revealed that only the error rates in SOA 0 ms (8.18 ± 5.94 %) were significantly higher than SOA 300 ms (6.22 ± 4.63 %), $t(24) = 2.46$, $p < 0.03$. In addition, when pooled like in our analysis above, error rates did not significantly differ between the short SOA (6.13 ± 4.30 %) and the long SOA (7.20 ± 4.94 %) conditions ($t(24) = 1.18$, $p = 0.25$). Results on error rates show that for each SOA condition the average error rate was below 10%.

Therefore, a complete analysis of all five SOAs supports the conclusions drawn above, i.e. that PRP dual-tasks demand the controlled attention function of WM because they demand executive functions coordinating task processing.

Turning to a more general discussion of this experiment, the TBRS model assumes that the task switching impairs the maintenance of information in WM. The amount of impairment is determined by the amount of time it occupies attention, i.e. general time-consuming attentional demands. Experiment 4 of Liefooghe et al., (2008) tested these attentional demands. Their paradigm incorporated task switching in a continuous span task. Participants were presented with time-constrained tasks in which they had to switch between two digit judgements while remembering letters. This particular experiment (number 4) manipulated not only the number of switches but also the degradation of the stimuli to which the digit-processing tasks were applied. They argued that stimulus degradation puts special demands on cognitive control. Results showed that the impairment in recall was of similar size for both low-switch lists with degraded stimuli and high-switch lists with normal stimuli (Liefooghe et al., 2008). Our argument is that the difference in recall performance is due to demands on executive functions. Therefore it could be that the stimulus degradation experiment of Liefooghe et al., (2008) applies to high level attention (i.e. executive functions) rather than low level attention. This is because in a more difficult perceptual task (with degraded stimulus), you may need to deploy higher level attentional resources (Lavie, Hirst, de Fockert, & Viding, 2004). According to the load theory of Lavie et al., (2004) the task difficulty determines the amount of resources needed. Difficult tasks require a lot of attentional resources and the selection is early to make the resources available. This means that an active mechanism of attentional control is needed to reject irrelevant distractors even when these are perceived. This attentional control depends on higher cognitive functions like WM that are required for actively maintaining current task processing properties to ensure the task is executed in the correct way (Lavie et al., 2004). Therefore, the degradation did not only prolong the perception stage but according to (Lavie et al., 2004) has an effect of the WM processes. According to Barch et al. (1997), a degradation manipulation primarily affects processes engaged during stimulus processing and response, and not during active maintenance. Thus, previous literature did not really specify what exactly these demands on “controlled attention” are, whether it can be “anything (like low-level attention)” or it needs to be “higher level executive functions”.

4.3 General Discussion on behavioural experiments

The present study was designed to investigate whether a central attentional bottleneck in the PRP paradigm demands additional executive control to resolve interference and coordinate the task processing (as predicted by the active scheduling theory). A series of experiments on the relationship between WM and dual-task with a focus on executive functions were reported. The cognitive load of dual-task performance was investigated by combining the PRP paradigm with a short-term memory task creating a complex WM span task. These tasks replicate the problem the cognitive system faces when trying to remember things whilst performing other tasks in the real world. The processing task can be seen as a distractor task by moving attention and resources away from the memory task and therefore less resources are devoted to memory rehearsal leading to poorer recall (Barrouillet & Camos, 2010; Brown et al., 2013). Also, there is a capacity limitation when performing one task after another as seen in dual-task experiments (Pashler, 1993, 1994). These experiments investigated the extent to which executive functions are needed to control this bottleneck processing. A second research question was to test whether these additional control processes are specifically related to the executive functions of WM. In each experiment participants were presented with time-constrained tasks in which they had to perform different manipulations of the dual-task PRP paradigm, one for each experiment, while remembering letters. The aim of the first set of experiments (experiment 1a, 1b) was to investigate the recall performance after performing a dual-task versus a single task. Results support the hypothesis that participants have poorer recall performance after performing a dual-task compared to a single task. This effect was present in all three tested memory loads and so was the classical PRP effect. Hence, the findings (PRP effect) are in accordance with an active scheduling account of processing two tasks with a capacity limited processing bottleneck. The executive functions required for active scheduling in the dual-task (but not the single tasks) occupy controlled attention for a longer period of time, leaving less time for rehearsal of the letters in memory.

Experiments 2 and 3 were performed to show the effect of experiment 1 whilst using a parametric modulation and therefore explore the additional demands further. The set of experiments 2 studied the manipulation of the order (fixed vs. random) in which the participants had to respond in the dual-task (De Jong, 1995; Luria & Meiran, 2003). Results of experiment 2c showed poorer recall performance after performing a random compared to a fixed task block condition. A follow-up experiment, experiment 2e, was conducted to rule out the possible effects of potential additional demands of the random dual-task condition compared with the fixed dual-task condition. Results showed that a high number of switches in the random order condition impose higher demands on controlled attention and therefore a reduced recall performance as compared to a low number of switches in the random order condition. These results are in line with the active scheduling account of bottleneck processing (De Jong, 1995; Luria & Meiran, 2003). A replication experiment was conducted to replicate the findings of experiment 2e and the evidence is ambiguous. The results of this replication showed that the recall performance after low switches is numerically larger than the recall performance after high switches, which is in line with our prediction, but unfortunately failed to reach significance. There are some points to note here. Firstly, most studies including the brief pilots showed effects according to the prediction. Secondly, the calculated power was based on experiment 1b with a very large RT difference between single task and dual-task. If the power is calculated based on experiment 2e, where the RT differences are much closer to those of 2f, the predicted sample size is much higher (>200). This is also in line with experiment 2c, i.e. the recall difference between random and fixed was sign but the RT difference was larger as well. Thus, the interpretation might be that experiment 2f lacks power, but testing >200 participants is out of scope for the revision. However, based on these arguments we think it is rather likely that there is an effect, but it is probably too small to be detected consistently with the current design. Therefore, we tentatively would interpret the combined finding of the experiment series 2 as further evidence that the additional processes involved in coordinating task processing at the stage of the bottleneck, such as inhibition, switching, and monitoring, are closely related to the executive functions requirements of WM.

In experiment 3, the SOA was manipulated using 5 different values which were later combined into two groups: short SOA versus long SOA condition. Shorter SOAs lead to higher demands on executive functions scheduling task processing than longer SOAs (Jiang, 2004; Logan & Gordon, 2001; Szameitat et al., 2011), because both tasks arrive at the bottleneck mechanisms closely in time and compete for task processing. Results on response time indicated the PRP effect which shows that a bottleneck had been present. Results of a multiple regression showed that SOA was not a significant predictor of recall performance but the ToT predictor was nearly significant. However, time on task for the short SOA dual-task condition was significantly shorter than the time on task for the long SOA condition. According to the TBRS theory, this should lead to a difference in recall performance for these two SOA conditions (Barrouillet & Camos, 2007). However, results showed that this prediction was not supported, countering the effects of more general task-related demands on controlled attention. This is an indicator that indeed demands on executive functions vary as predicted by the active scheduling account (i.e. shorter SOA demands higher executive functions). Furthermore, it indicates that these executive functions demand the controlled attention of WM.

4.4 Conclusion on behavioural experiments

These chapters aimed at understanding the role of WM in dual-task performance and the need for executive functions in both tasks. In order to provide an answer to this research question the PRP dual-task paradigm was combined with a short-term memory span task to create a complex WM task. Experiment 1b showed that memory performance is lower after performing a dual-task compared to single task. The next experiment revealed that participants had poorer recall performance after performing a random dual-task block versus a fixed dual-task block and was elaborated upon in experiment 2e that performance in a high switch random dual-task block is lower than in a low switch random dual-task condition. In addition, a third experiment was conducted and used a SOA manipulation. Results showed that time on task only (general task-related demands on controlled attention) cannot explain the recall performance and executive functions are needed as well. It is still likely that there is an effect on recall performance between different switch conditions, but at this point in time it is not clear and future research is needed to investigate this more. Despite inconclusiveness, we believe that a task condition imposing higher demands on executive functions required to coordinate processing at the stage of the bottleneck has a negative impact on memory performance. All together these experiments support the assumption that PRP dual-tasks demand executive functions and more specifically that these demands are related to the executive functions of WM.

Chapter 5 : Neuroimaging literature review

5.1 Introduction

The behavioural experiments described in the previous chapters showed that recall performance is lower after performing a dual-task compared to a single task in the retention interval. All together these experiments support the assumption that PRP dual-tasks demand executive functions and that these are related to the executive functions of WM. Hence, it is not about general task-related demands on attention, but more specifically about the executive functions that control the task processes. This shows that that PRP dual-tasks demand additional control processes and moreover that these control processes are related to the executive functions of WM. The next step is to understand the functional neuroanatomical correlates of these executive functions. In particular, the question is whether the executive functions of PRP and WM are subserved by similar brain areas. In order to understand the brain mechanisms of executive functions in more detail, it is necessary to review the current neuroimaging literature on both multitasking and WM.

5.2 Neuroimaging research on multitasking

As mentioned before, dual-task paradigms have commonly been used to study executive functions. However, the exact neural implementation of these executive functions is still unresolved. Previous neuroimaging research gives contradictory evidence with respect to the neural correlates of executive functioning and dual-task processing which might be due to the different paradigms (which not always necessarily ensure interference) used by different researchers. However, most neuroscientific research using the PRP paradigm suggests specific dual-task activation as compared to single task activation.

Before reviewing the evidence, I would like to define the concept of dual-task specific activation since this can be evident in different ways. First, dual-task specific activation can be evident as activation of a brain area which is not activated by any of the single tasks, i.e. it would be an area newly/solely activated by the dual-task. Second, dual-task specific activation can be evident in brain areas which are activated by one or both single-tasks. In that case, the activation in the dual-task needs to be higher than those of both single-tasks combined, i.e. it needs to be over-additive.

Dual- and single tasks may activate the same brain area because the aim is to localize executive functions, for instance inhibition, which is, as explained in Chapter 1, needed specifically for the coordination of dual-task processing. However, inhibition is a generic executive sub-function which may be involved in various other tasks (e.g. task switching) including potentially very simple non-dual tasks (e.g. Stroop, go/no-go tasks). In these cases, a brain area associated with inhibition might be activated already by the single task, but may be activated (over-additively) stronger by the dual-task due to the additional dual-task specific demands on inhibition. Thus, whether a dual-task specific area appears as a newly activated area or as an over-additive activation in an area already activated by one or both single-tasks merely depends on the nature of the single-tasks.

Szameitat, Schubert, Müller, & Von Cramon (2002) tested for dual-task related activation by using the PRP paradigm, which ensures the occurrence of interference and therefore the presence of executive functions. Twelve participants performed an auditory and visual three-choice response task either as single tasks or simultaneously as dual-tasks. In their study they used two different methods to analyse the neuroimaging data. First, they used the cognitive subtraction method where two conditions of brain states are presumed to differ only in one discrete feature (the independent variable) (Harrison & Pantelis, 2010). Based on this, dual-task activation is assessed by testing whether both tasks interact with each other when performed simultaneously. In other words, it is tested whether there is surplus, or over-additive, activation in the dual-task condition as compared to the summed activation induced by the single task conditions (Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999). This method takes into account that areas which are identified as dual-task related areas might already be involved in single task processing too but are more strongly activated in the processing of the dual-task.

However, this method of cognitive subtraction is based on the assumption of pure insertion (Donders, 1969). This assumption states that a single cognitive process (a second single task) can be inserted into a task without affecting the remaining processes. In other words, there are no interactions among the cognitive components of a task which is an issue that has been questioned by researchers (Friston et al., 1996; Sternberg, 1969). Inserting a second task to create a dual-task might, in addition to executive functions, also change the general perceptual processes of the first task. To circumvent problems with this, one can use the parametric manipulation method. According to that method, one factor that affects the operation of a single process is varied and it is determined whether this manipulation results in systematic activation changes of certain brain areas. If this is the case, then these areas can be linked to the manipulated process (Szameitat, Schubert, Müller, & Von Cramon, 2002). In other words, one does not attempt to include or exclude the process of interest but rather to modulate the degree to which the process is present. This allows one to characterize the relationship between the process of interest and the regional brain activation (Garavan, Ross, Li, & Stein, 2000).

For the fMRI results, the method of cognitive subtraction showed that both single tasks had rather small activations in the lateral prefrontal cortex, namely in the middle frontal gyrus (MFG) for the auditory task and the left MFG and the right superior frontal gyrus (SFG) for the visual task

(Szameitat, Schubert, Müller, & Von Cramon, 2002). The interaction contrasts revealed a large left prefrontal cluster containing the inferior frontal sulcus (IFS), the MFG and the superior frontal sulcus (SFS). Furthermore, analysis showed that the activation peaks in the single tasks were located more anteriorly than the activation peaks in the dual-task. This suggests that the single and dual-tasks recruited different regions in the lateral prefrontal cortex (Szameitat, Schubert, Müller, & Von Cramon, 2002).

Szameitat, Schubert, Müller, & Von Cramon (2002) tested whether the findings of the cognitive subtraction method could be validated using the parametric manipulation method. A random-order dual-task condition, similar to the one used in Chapter 3, was introduced. It was predicted that dual-task related areas activated by the dual-task fixed order condition would show higher activation in the dual-task random order condition since this random order condition increases the role of inhibition and switching (De Jong, 1995). First, results of the cognitive subtraction method showed similar areas for dual-task random order as for dual-task fixed order. Second, the contrast between dual-task random order and fixed order (a direct comparison) showed higher activation in the dual-task random order condition in all areas activated in the dual-task fixed order condition. In summary, results showed that dual-task related activation cannot be reduced to the sum of the single task activations. Therefore, these lateral prefrontal areas are related to interference in task processing in a PRP dual-task. Also, the activation in the single tasks was differentially located which demonstrates that dual-task-specific activation can be independent of single task-related activation. This dual-task activation was shown with two different methods, cognitive subtraction and parametric manipulation.

More evidence for dual-task activation when comparing dual-task activation to the sum of the single tasks activation was found in prefrontal, temporal, parietal and occipital cortices in another study using the PRP paradigm (Schubert & Szameitat, 2003). Participants (N = 11) performed two choice reaction tasks simultaneously and were asked to determine a target square from three squares presented to them and whether a pitch tone was low, moderate or high. In the dual-task condition, three different SOA conditions were used, 50, 125 and 200 ms. Behavioural results showed the expected PRP effect and increased RT and error rates for the dual-task as compared to the single task conditions. Activation in the overlapping dual-task condition was compared with the summed activation of the single tasks, similar analysis as Szameitat, Schubert, Müller, & Von Cramon (2002), and here dual-task related activation was shown in the lateral PFC in regions along the left IFS up to the precentral sulcus, middle occipital gyrus, temporal gyrus and precuneus. This data suggests again that processing of overlapping dual-tasks requires an extensive network of brain areas. The main focus of dual-task activation in prefrontal areas was again found in regions around the left IFS which might reflect increased activity related to managing interfering information in order to execute the appropriate responses. This suggests that inhibition and switching, two functions of the executive system, are linked to the LPFC.

These findings were confirmed by a later study of Szameitat and colleagues on the neural correlates of task order coordination in dual-tasks (Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2006). This task order scheduling is the control process of the order in which two component tasks are processed by the bottleneck. In this study, participants (N = 15) performed a PRP dual-task of two 3-choice reaction tasks, one auditory and one visual with a SOA of 200 ms. Participants were required to respond to the tasks in the order of their presentation, but the presentation order of the tasks changed randomly. Trials in which the present task order changed as compared to the previous trial impose higher demands on task coordination than same-order trials do (see Chapter 3). Results showed that different-order trials showed stronger activation along the posterior part of the left IFS as well as the right posterior MFG compared to same-order trials. This is supporting evidence that one of the functions of the LPFC is the temporal coordination of tasks. The areas that were higher activated during different-order trials are already strongly activated by same-order trials. Thus, the areas do not reflect purely the reorganisation of the order, but are involved in other processes as well. This study is also in accordance with the active scheduling account, which assumes that task processing is actively monitored and scheduled and that task order can be prepared in advance. If the preparation is wrong, re-organization of the task processing takes place which results in increased cognitive demands (executive functions) (De Jong, 1995; Luria & Meiran, 2003). This active scheduling is needed to organize the task processing at the bottleneck.

This was further investigated by Stelzel et al. (2008) who explored the effect of task order control and task set maintenance. This task set maintenance which includes the stimulus and response sets, the task context and rules, has to be actively maintained in WM when performing a behavioural task (Logan & Gordon, 2001; Miller, 2000). Both functions were manipulated in a 2x2 parametric design by using fixed and random orders for the task order control and using different set sizes (4 and 8) for the stimulus-response mappings. Dual-task costs were greater with a higher set size and the random task. The fMRI results revealed a functional neuroanatomical dissociation for the LPFC activation. Increasing the demands on task order (random dual-task compared to fixed dual-task) revealed regions surrounding the IFS and the MFG. However, increased demands in task set maintenance only revealed activation in one region of the LPFC, namely the left anterior insula. Differences in activation between task order control and task set maintenance were also found outside the LPFC, in the premotor cortices. Results showed more rostral premotor activity for task order control and more caudal premotor activity for task set maintenance. These results showed that task order control can be dissociated from task set maintenance.

A similar conclusion as Szameitat, Schubert, Müller, & von Cramon (2002) was found by Herath, Klingberg, Young, Amunts, & Roland (2001) whose research indicated that dual-task performance elicited additional cortical regions (IFG) which are not activated by the component tasks. This was tested (N = 10) by using two simple RT tasks (not choice RT tasks and hence there is no response selection stage), a single visual RT task and a single somatosensory RT task and they were also combined as dual-task with different long and short SOAs. The two single tasks mainly activated motor regions which included the supplementary motor area (SMA) and cingulate motor areas (CMA). When both tasks were performed simultaneously, the same motor areas were activated, but in addition the right inferior frontal gyrus was activated in the dual-task condition.

The results of Szameitat, Schubert, Müller, & Von Cramon (2002)'s study were further confirmed by a similar study who also calculated dual-task specific activation by subtracting the single task from the dual-task activation. Dual-task specific activation was found in prefrontal and parietal cortices when looking at stimulus-response modality compatibility (Stelzel, Schumacher, Schubert, & D'Esposito, 2006). In more detail, participants (N = 13) performed modality-compatible (e.g. visual-manual or auditory-vocal) and modality-incompatible (e.g. visual-vocal or auditory-manual) single and dual-tasks. Higher dual-task costs were found for the modality-incompatible as compared to the modality-compatible tasks. fMRI results showed dual-task specific activations in the prefrontal and parietal cortices and more specifically in the left IFS, SFS, precentral sulcus, ACC and left preSMA. Furthermore, the data revealed a higher activity along the IFS in the modality-incompatible versus the modality-compatible dual-tasks. This suggests that besides temporal order coordination (Szameitat et al., 2006) the IFS is also involved in the coordination of concurrent mapping processes between stimulus and response modalities in a dual-task. Therefore, the results of this study suggest that the IFS plays a general role in the coordination of interfering task processes in dual-task situations (Stelzel et al., 2006).

So far, these results support that prefrontal and superior parietal cortices are involved in the coordination of processing two tasks in the PRP paradigm (Miller, 2000; Szameitat, Schubert, Müller, & Von Cramon, 2002). Also, results indicate that executive functions play an important role when performing dual-tasks as compared to single task performance. There is more neural activity, as reflected by more activation in certain brain areas and/or different brain areas when there is interference between dual tasks. Thus, PRP tasks demand the central executive system which activates a fronto-parietal network in the brain (De Jong, 1995; Dux et al., 2006; Schubert & Szameitat, 2003; Stelzel et al., 2006; Szameitat, Schubert, Müller, & von Cramon, 2002; Szameitat et al., 2016).

However, other dual-task brain imaging research, notably mostly using other tasks than the PRP task, has shown different findings. Some have suggested that a possible mechanism of dual-task interference is that the two single tasks activate the same functional brain areas (Adcock et al., 2000; Klingberg, 1998, 2000). In the study of Adcock et al., (2000) two dual-task paradigms were used, each having a common auditory component (verbal categorization task) but varied with respect to the visual component task (either mental rotation task or object identification task). They searched for over-additive dual-task specific areas, but did not find any. Four regions of interest (ROIs) showed some evidence of stronger activation in dual-tasks in percent signal change comparisons, namely dorsomedial frontal cortex near the supplementary motor area (SMA), anterior cingulate cortex (ACC), left MFG and the left lateral occipital sulcus. All activation was equal to the additive summation of the single task activations, i.e. dual-task = single task 1 + single task 2 (thus, not over-additive). Therefore, the main finding is that there was no evidence of a neural locus for executive functions in the prefrontal cortex or elsewhere which is selectively activated by dual-task performance. It was suggested that bottom-up mechanisms may underlie other operations sometimes characterized as executive functions. One potential reason for not finding evidence for executive functions by Adcock et al. (2000) might be that the behavioural results showed no or rather small performance decrements in the dual-task condition as compared to the single task conditions. This may indicate that participants processed the tasks without task interference and hence there would be no need for executive control and consequently no executive functions related areas are activated.

Another study which questions the existence of dual-task specific brain activation used two different tasks (sentence reading and short-term memory of five words) either performed separately or simultaneously to examine the neural substrates of dual-task coordination (Bunge et al., 2000). This is a complex WM span task (reading span task). The sentence reading task required participants (N = 8) to read sentences and deciding whether the statement was right or wrong. The short-term memory task consisted of the presentation of five sentences and participants were required to recall the last word of each sentence after all sentences had been presented. Behaviourally, dual-task performance was associated with performance decrements relative to performing either component task. Dual-task performance was associated with increased activation in prefrontal areas (right MFG, left IFG, bilateral ACC) and left parietal cortex. These brain areas were also found in the single tasks but with reduced activations, but the dual-task activation did not lead to over-additive activation. Therefore, Adcock et al., (2000) and Bunge et al., (2000) searched for newly activated areas only by the dual-task condition. However, that logic can be questioned (see above and cf. (Szameitat et al., 2011)). For both studies it is highly plausible to assume that already the single tasks would need some executive functions, because the single tasks themselves were quite complex tasks.

Another study using PET imaging studied the capacity limitation of WM while participants performed two cognitive tasks, both separately and simultaneously (Goldberg et al., 1998). One task was the Wisconsin Card Sorting Test, and the other was a rapidly paced auditory verbal shadowing task. In the latter task participants repeated aloud words that they heard, i.e. they shadowed words. It has been suggested that these tasks demand attention and need the use of the central executive system to coordinate the two tasks (Baddeley, 1998). Significant performance decrements arose when both tasks were performed simultaneously compared to performing them as single tasks which indicated that cognitive load had been increased. PET results showed that when the two tasks were performed simultaneously, there was less prefrontal activation then when they were performed as single tasks. This suggests that increased cognitive workload does not necessarily always increase the recruitment of executive functions, but rather that prefrontal cortex activation might even get attenuated with regards to increased demands for stimulus processing and response selection (Goldberg et al., 1998). The reason for this finding might be overload, i.e. at very high cognitive loads, the PFC activity actually decreases. This was also found in another study who disentangled memory load with task difficulty (Barch et al., 1997).

Another study comparing dual-task and single task performance used two non-working memory single tasks, a spatial-rotation task and a semantic-judgement task (D'Esposito et al., 1995). This study used the terminology central executive system of WM but basically it is a dual-task paradigm. Behavioural results again indicated a decrease in performance for the dual-task compared to the single tasks alone. Brain activation was measured during the concurrent and separate performance of the two tasks. Results (N = 6 subjects) showed that there was a significant increased activation bilaterally in the DLPFC when comparing the dual-task to the single task conditions and neither task activated PFC when performed alone. Also, the ACC was activated in most subjects only during the dual-task which has been proposed to be critical for response selection amongst competing tasks.

While it is well known that concurrent response-selection demands create interference which demands executive functions, Klingberg (1998) investigated whether concurrent short-term memory (STM) demands are sufficient to demand executive functions. This is interesting, because the current study combines concurrent STM demands with response-selection demands, i.e. the current study bridges Klingberg's approach with the more traditional PRP studies. One of the tasks was a visual WM task (go/no go) whereby participants had to compare each target luminance level with the previous one and respond if the luminance level was lower than the previous, otherwise no response had to be given. The other task was an auditory WM task (go/no go) whereby participants had to only respond when the target tone was lower in frequency than the previous tone. In the dual-task condition, both WM tasks were performed simultaneously. The onset of a target tone was always separated by at least 1000 ms from a target luminance level and vice versa. Therefore, the response to the stimuli did not coincide for the auditory and visual tasks. The delay period between stimuli, which is the period when the participants needed to keep the sensory information online, overlapped between the auditory and visual task. In the control condition, auditory and visual stimuli were presented but no response was required (passive stimuli). Compared to the control condition, PET results showed that the auditory and visual WM tasks activated areas in the STG and occipital pole respectively known to be sensory-specific. Besides these, both tasks also activated areas in the DLPFC, inferior parietal and cingulate cortex. No separate area was activated only in the dual-task and hence there was no evidence for dual-task specific cognitive processes such as divided attention or task-coordination (Klingberg, 1998). In conclusion, the two actions are concurrent, but just the concurrent demands on STM seem not sufficient to create interference. Thus, pure parallel STM demands are not sufficient and for the current study the question remains open whether the combination of STM demands with response-selection demands require executive functions.

A study conducted by Erickson et al. (2005) also reported no additional brain areas related to dual-task performance. In this study, brain regions involved in dual-task processes were investigated in a paradigm that could minimize effects related to preparation. For this, single and dual-task trials were randomly and unpredictably intermixed for one block (mixed block) and also presented in isolation of one another during other blocks. For the single tasks a colour discrimination and a letter discrimination task were used. Making the sequence of trials unpredictable was important because the brain regions associated with task preparation are modulated by timing and predictably of the trial sequence, hence an unpredictable sequence was used in the mixed block. Behavioural results indicated that participants (N = 33) were slower and made more mistakes in the dual-task compared to the single tasks as well as for the comparison between mixed and pure trials. After minimizing the effects of preparation a large network of brain regions involving the left and right inferior PFC, dorsal ACC, left and right inferior parietal and superior parietal lobules was found. Importantly, the brain regions active for the dual-task conditions were similar to regions active in the single task conditions only with a greater magnitude which, if over-additive, would indicate dual-task specific activation. But the researchers compared the dual-task to the mean of the single tasks (and not the sum). Thus, it remains unclear whether Erickson et al. (2005) found additive or over-additive activation in the dual-task.

Research on memory load and task performance was investigated by Jaeggi et al. (2003). The n-back paradigm was used at four levels of difficulty with auditory-verbal and visual-nonverbal material. These were performed as both single and dual-tasks. fMRI results showed enhanced activation in the DLPFC for both single and dual-tasks with increasing load. There was no interaction between memory load and activation in single and dual-tasks. However, when the sum of the activation in the single tasks was compared with the activation in the dual-task, the increase of DLPFC was smaller in the dual-task compared to the summed single tasks, i.e., under-additivity (Jaeggi et al., 2003). This seems to suggest that dual-tasks do not need additional areas (e.g.

executive functions) compared to single tasks and contradicts most findings in this section on whether PRP dual-tasks need executive functions.

5.2.1 Summary of neuroimaging research on multitasking

This section has presented research in support of dual-task specific activation and research against this idea. In the well-controlled PRP paradigm, which can ensure occurrence of interference on a response-level (and similar paradigms which can also ensure this), dual-task specific activation is shown. Studies which fail to show dual-task activation are often those who a) do not show behavioural interference (e.g. Adcock et al., (2000)) and/or b) have concurrent demands which are not response-related (e.g. concurrent STM demands like Klingberg (1998)). In this thesis, the PRP paradigm is used for which dual-task specific activation has consistently been shown (Schubert & Szameitat, 2003; Stelzel et al., 2008; Szameitat, Schubert, Müller, & von Cramon, 2002) and combines STM demands with response-selection demands (PRP paradigm) to examine the demands on executive functions. Whilst this section has investigated research on multitasking, the next section focuses on neuroimaging research on the second strand in the current thesis which is WM.

5.3 Neuroimaging research on working memory

WM is the short term storage of information (maintenance) and executive functions (processing, coordinating functions like inhibition, switching, monitoring). It is a central cognitive function and operates when information has to be retained and manipulated over a short period of time which then often leads to a response, but not necessarily. The central executive integrates information from different sources. An important characteristic of the executive system is that its resources are limited and divided into different processing and storage functions. Neuroimaging studies on the concept of WM have shown that the prefrontal cortex is involved in human WM. The next paragraph focuses on two specific regions namely the DLPFC and ACC which have been shown to be involved in the central executive system (D'Esposito et al., 1995).

The DLPFC and the ACC are significant brain areas in the prefrontal cortex and have been suggested to be involved with the central executive system by monitoring performance and detecting errors (Carter et al., 1998; D'Esposito et al., 1995). Carter et al. (1998) used fMRI to examine the functioning of the ACC. Participants (N = 13) performed variants of the Continuous Performance Test that was designed to both increase error rates and manipulate response competition (Carter et al., 1998). Results showed ACC activity during error responses, but also during correct responses under conditions of increased response competition. This suggest that the ACC detects conditions under which errors are likely to occur rather than the errors themselves

(Carter et al., 1998). This might mean that the ACC is associated with the inhibition and monitoring functions of the executive system during task processing (Carter et al., 1998). This was further investigated by MacDonald, Cohen, Stenger, & Carter (2000) who used fMRI to study a task-switching version of the Stroop task to test whether two aspects of cognitive control, implementation and performance monitoring, have distinct neural bases in the brain. Both tasks used in this study (word/colour) can be congruent and incongruent. Congruent refers to the combination of colour-word and ink-colour, which is an automatic response. Participants (N = 12) were given an instruction before each trial indicating whether to read the word (congruent) or to name the colour (incongruent, which requires more cognitive control (inhibition)) after which the stimulus was presented. A double dissociation was found in the neuroimaging results for the DLPFC and ACC in cognitive control. The left DLPFC (Brodmann Area (BA) 9) was more activated during task preparation for colour naming than for word reading, which is associated with implementation of control. However, the ACC (BA 24 and 32) was more active when responding to incongruent stimuli which is consistent with a role in monitoring performance and response conflict (MacDonald et al., 2000). Avoiding errors is an important factor in the PRP paradigm where the second task has to be inhibited until the first task has been executed and from this research it seems that the ACC plays an important role in this part of executive functions. Similar findings on the role of the ACC and cognitive control have been reported by Matsumoto & Tanaka (2004). They looked for evidence of a direction connection between the detection of conflicts in the ACC and subsequent greater control recruited in the lateral PFC. For this, they used the Stroop task and found that ACC activity in an incongruent trial had a positive correlation with the LPFC activity in the next trial. This suggests that the ACC recruits control in the LPFC based on conflict monitoring (Matsumoto & Tanaka, 2004). This link was further explored in a meta-analysis by Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis (2004). Their findings show that the posterior medial frontal cortex (pMFC) is associated with the detection of unfavourable outcomes, response errors and response conflict. Furthermore, they describe a link between activity in this area and subsequent adjustments in performance which comes from interactions between the pMFC (monitoring-related activity) and the LPFC (implementing performance adjustments) (Ridderinkhof et al., 2004). Other reviews have indicated a similar role for the ACC in relating actions to their consequences and for the DLPFC in relation to executive control and behavioural adaptions (Mansouri, Tanaka, & Buckley, 2009; Rushworth, Walton, Kennerley, & Bannerman, 2004). Thus, the ACC and the LPFC play an important role in executive functions.

Other research on the need for executive functions used STM tasks. Three STM tasks were used in a study by Salmon et al. (1996) one of which was a control task where participants had to remember Korean letters and judge whether a probe letter was presented in the memorised sequence. The first memory task was a phonological STM task where participants had to rehearse six consonants serially and detect whether a target consonant was present in the sequence. The second memory task was an updating WM task, where lists of different length were presented and participants had to rehearse the consonants serially and only remember the last six items. Then they had to judge whether a consonant was present in the last six consonants of that particular list. Results from the PET study showed increased regional cerebral blood flow (rCBF) in a set of frontal and parietal regions (right mid-dorsolateral PFC (BA 9), left middle frontal regions (BA 46 and possibly BA 10), the right frontal pole, right inferior parietal gyri) when comparing the WM updating task with the phonological STM task. These results show that the phonological loop is able to store only a limited number of items in the correct order but that the central executive system may increase this number by either increasing the efficiency of the phonological loop or by using its own central storage capacity (Salmon et al., 1996). WM is STM storage like the phonological loop plus executive functions. Therefore, this study confirms that the prefrontal cortex is a key structure for the central executive system. This is relevant for the current study where memory updating needs to occur during the performance of a PRP paradigm.

Smith & Jonides (1999) conducted a review on WM and used the same definition as in this thesis. WM is a system for temporary storage (short-term) and manipulation of information (executive processes that operate on the contents of the temporary storage). Neuroimaging results show that storage and executive functions are major roles of the frontal cortex. There is a distinction within the activations of the frontal cortex: storage for verbal material activates Broca's area and left premotor areas whilst storage for spatial information activates the right premotor cortex. These areas mediate the rehearsal processes for verbal and spatial information (Smith & Jonides, 1999). With regards to executive functions which involve selection of attention and task management, both the ACC and the DLPFC showed activation which shows that the executive functions are differently located to the storage areas. Again, this shows the role of executive functions in prefrontal areas of the brain.

This difference in hemisphere activation was also reported by D'Esposito et al. (1998). This meta-analysis on the type of material held in WM (spatial vs non-spatial) did not find a dorsal-ventral subdivision of the prefrontal cortex, which is found in monkey lesion studies, but suggested a hemispheric division: right for spatial WM and left for non-spatial WM. Additionally, in their own experiment where participants had to perform spatial and verbal (non-spatial) 2-back WM tasks, they found activation in the right MFG, BA 46 in both spatial and non-spatial WM.

Using individual differences and attention control, Kane & Engle (2002) in their review provided an executive-attention framework for research on working memory capacity and the prefrontal cortex (Engle, Tuholski, Laughlin, & Conway, 1999; Kane & Engle, 2002). It was proposed that WM is a system consisting of STM and executive attention components in line with our definition of WM presented earlier. The focus was on the DLPFC and indicated that this area has a unique role in actively maintaining access to stimulus representations in tasks with interference (dual-tasks) (Kane & Engle, 2002). In other words, the function of the DLPFC is to sustain the activation of memory representations when the attentional focus is drawn away due to distractors (dual-tasks). This is closely related to our complex WM span tasks where memory representations need to be actively maintained when participants perform the PRP dual-task in the retention interval.

Neuroimaging studies have used variations of several common tasks most of which require multiple executive processes. A meta-analyses of 60 neuroimaging (MRI and PET) studies on WM was conducted to shed more light on how WM is represented in the brain (Wager & Smith, 2003). WM was considered to consist of three types of storage (spatial, verbal and object) and three types of executive function processes (updating of WM, manipulation of information in WM and memory for temporal order). Main effects of both types of storage and types of executive functions as well interactions between the two types were investigated. Results indicated that WM representations in the frontal cortex are organized by executive function process rather than by material type (storage). Furthermore, results suggested that tasks that require continuous updating and memory for the sequential order of items involve inferior and superior frontal cortex on WM items. This study has shown again how the executive functions activate the frontal cortex.

A review on the commonalities between WM and STM and their respective brain areas by Linden (2007) revealed similar findings. Key findings included the activation of frontal cortex for visuo-spatial information in WM, which mirrors the dorsal and ventral pathways known in perceptual processing. It suggested, in line with earlier mentioned research, that the central executive system is not implemented in a single unitary brain network, but that it is a network of mainly frontal and parietal regions and sometimes also premotor areas (Linden, 2007). Another meta-analysis on brain regions commonly and differently active during several WM tasks was performed by Rottschy et al. (2012). 189 fMRI experiments on healthy participants were included and the main effect showed again a widespread bilateral fronto-parietal network. Results also showed more specific effects such as activity in Broca’s area during verbal tasks, ventral and dorsal premotor cortex involvement in memory for object identification and location, and LPFC for task set (anterior) and load effects. Again, this review showed evidence for a consistent core network for WM and is in line with previous studies.

More research on brain regions involved in WM task performance showed again increased activity in LPFC, ACC and parietal cortices during the encoding, maintenance and task coordination stages of task performance in a complex WM span task (Chein, Moore, & Conway, 2011). They used two processing tasks, a lexical decision and a symmetric decision task whereby participants either had to indicate whether the presented string of letters formed a word (lexical) or had to indicate whether a presented coloured matric was symmetrical about the vertical axis. Besides this there were two different types of storage (memory) tasks used, letters and location tasks whereby participants either maintained a sequence of 4 items for recall or remembered the locations of cells in a 4x4 matrix. Activity in anterior prefrontal and medial temporal lobe regions was associated with both verbal and spatial recall from WM. For both processing tasks, there was an increased activity in lateral prefrontal, anterior cingulate and parietal cortices during the encoding, maintenance and coordination phase of task performance (Chein et al., 2011). Thus, for both processing task and WM, increased activity in prefrontal areas was found. These are interesting findings since the current study uses a complex WM span tasks with the stages encoding, retention interval (maintenance of items of the encoding stage and coordinating the processing of the PRP tasks) and recall.

The operation span, a well-known complex WM task, was used in a PET study by Smith et al. (2001). In this task participants perform a memory task (remembering target words) while simultaneously indicating whether simple equations are correct or not. In this particular study, young and senior participants performed the task and both showed costs when performing the operation task compared to performing either the memory or the equation task separately. PET results showed that the DLPFC was active in the dual-task but not in the component tasks which suggests that the executive components of memory storage (during the distractor equation task, e.g. the retention interval) recruit left DLPFC for certain subject groups (seniors and only young performers who performed poorly on the task) but no prefrontal regions were active in the retention interval for young, good performers. In other words, poor performance led to higher activation. This might indicate that activation in PFC reflect differences in cognitive demands in dual-task (Smith et al., 2001). Alternatively, it could be that young participants who performed well had very small PFC activation which was not detected (null-finding). However, the results suggest that in LPFC, lower performance is associated with higher brain activation.

Prefrontal activations but also ACC activations were found in another study on the operation span task (Kondo et al., 2004). fMRI results showed brain activation for the dual-task in ACC, left PFC, left inferior frontal cortex. When subtracting activations of the single task conditions from the dual-task activations, the ACC and precuneus were activated for participants with a high WM score. Together these results suggested that the ACC and left PFC (a cingulo-frontal network) are involved in the central executive functions of shifting of attention and manipulating internal representations during the operation span task.

Similar prefrontral activations were found when a different complex WM span task was used, i.e. the listening span task. In more detail, the listening span task revealed activations in the left middle and inferior PFC, dorsal site of the ACC and STG (Osaka et al., 2003). The activity in the

PFC was significantly increased when participants performed the listening span task as compared to preforming the listening task only (i.e. dual-task minus one single task), again showing increased activation caused by increased demands and dividing attentional resources in the dual-task. This shows again the work of the executive system and in this case it is responsible for the allocation and coordination of attentional resources in the language area (inferior PFC) (Baddeley, 1996a). Again, it was proposed that the ACC activation found in this experiment not only reflects strategic manipulation but also attentional control (Osaka et al., 2003).

One issue related to the dissociation of specific WM demands is its relation to difficulty. It has been suggested that demands in WM are dissociated from task difficulty in the brain. For instance, a degradation manipulation primarily affects processes engaged during perception of the stimulus, because it is more difficult to perceive the stimulus when it is degraded compared to when it is presented normally. However, once the stimulus is perceived there is no more difficulty and hence degradation does not affect active maintenance, e.g. WM (Barch et al., 1997). In their study they explored the dissociation between demands in WM and task difficulty. For this, they used a variant of the Continuous Performance Test where subjects have to monitor a sequence of single letters, for the presence of a pre-specified probe (e.g. X) and respond to it whenever it follows a particular cue (e.g. A). In order to give a correct response, memory of the prior stimulus is required. WM demand was manipulated by varying the delay between the cue and probe stimuli. Task difficulty was manipulated independently of WM by using a stimulus degradation manipulation. Hence a 2 (short vs long delay for WM) x 2 (degraded vs non-degraded stimuli) factorial design was used. Imaging results (N = 11) showed increased activity in DLPFC, left inferior frontal gyrus (Broca's area) and left posterior parietal lobule during task conditions that placed demands on active maintenance relative to control conditions matched for task difficulty. This activation sustained over the entire retention interval and did not increase when task difficulty was manipulated independently of WM demand. In contrast, there was increased activity in the ACC, right inferior frontal cortex and a subcortical region in response to task difficulty but not WM demands. There were no main effects of task difficulty in any of the regions activated due to WM demands. Therefore, a double dissociation was found between regions responding to WM and to task difficulty with a specific involvement of DLPFC for WM demands.

5.3.1 Summary of neuroimaging research on working memory

This section has presented research on the functional neuroanatomical correlates of WM (executive functions and storage of information). Complex WM span tasks are often used to study this. When using complex WM span tasks (using inhibition, shifting and updating) such as the operation and listening span task, prefrontal areas as well as ACC are often activated (Chein et al., 2011; Kondo et al., 2004; Osaka et al., 2003; Smith et al., 2001). Other research on the role of the

PFC and cognitive control and executive functions has found a profound role for the DLPFC and the ACC in monitoring performance and detecting errors as well as implementing behavioural adjustments (Carter et al., 1998; MacDonald et al., 2000; Mansouri et al., 2009; Rushworth et al., 2004).

5.4 Summary of neuroimaging literature

The aim of the current thesis is to answer the question whether the executive functions involved in PRP dual-tasks and WM are related or not. The behavioural studies provided strong evidence that they are related. Previous imaging studies support this conclusion, because the majority of neuroimaging studies indicate that WM and dual-tasks (more specifically PRP paradigms) are both associated with frontal regions such as the DLPFC (mainly MFG), VLPFC (mainly IFG), and medial PFC (mainly ACC). However, this conclusion is drawn on the basis of different studies, and when the results are scrutinised in more detail, differences in the exact activation patterns can be observed across studies. Therefore, to provide stronger support for the hypothesis that the executive functions of WM and PRP are related, I conducted two fMRI studies in which subjects performed both tasks, PRP and WM, within the same session (within-subject design). This allows to test much more accurately whether PRP and WM activate similar (overlapping) areas in the PFC or not. If both paradigms activate similar regions or show a strong overlap, then this would be support for the idea that both paradigms rely on the same cognitive processes, i.e. they rely on the same executive system. The next two chapters will address these questions, but first a behavioural pilot was conducted to make sure the paradigm used so far is compatible with the MRI scanner.

Chapter 6 : fMRI Study 1

6.1 Experiment 4a: Behavioural pilot for fMRI study 1

The question of this thesis is the link between PRP and WM. The behavioural studies outlined from Chapters 2 till 4 showed that there is a link. In more detail, experiment 1b (see Chapter 2.3) showed that WM is affected more by dual-task than by single task, indicating that both rely on the same cognitive processes. This is probably executive functions/controlled attention. The current experiment aims to corroborate this conclusion by brain imaging. Therefore, as research question I would ask “Do PRP and WM have similar functional neuroanatomical correlates?” If yes, then this supports the idea that they both rely on the same executive functions. For this, basically experiment 1b is conducted in the MRI scanner. If WM and PRP dual-task rely on the same mental processes, I predict that they activate the same brain areas. This hypothesis is supported by previous research which has shown that dual-task and WM both activate similar areas in the PFC (see Chapter 5). However, it has never been tested directly. Before conducting this experiment in the scanner, the paradigm needed to be adjusted. The behavioural pilot aimed at testing whether the behavioural findings still exist with an fMRI suitable paradigm. In particular the number of trials and therefore the duration of the retention interval was changed as compared to experiment 1b. Participants have to memorize the letters whilst performing the PRP paradigm in the retention interval and therefore the primary interest is the retention period. In experiment 1b, 5 trials each lasting 2000 ms were used during the retention interval. This retention interval of 10 seconds is not optimal in an fMRI blocked design (Huettel, Song, & McCarthy, 2004). Therefore, this behavioural pilot was conducted to see whether recall performance is more affected by dual-task compared with single task processing when using a longer retention interval (more trials).

6.1.1 Method

6.1.1.1 Participants

Seven (5 female) participants (mean age: 21 years, SD = 2.1, range 19-25 years) took part in the study after having given written informed consent. The study was approved by Brunel University’s College of Health and Life Sciences Ethics Committee and participants received course credits for participation. The information leaflet, consent form, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 5.

6.1.1.2 Tasks

The experiment again consisted of a WM span task with preload procedure which consisted of the following phases: cue, memory encoding phase, retention interval processing phase (single versus dual-task), recall phase and feedback. The memory encoding phase, recall phase and feedback were exactly the same as experiment 1b. The cue was shown for 4 seconds and the feedback was shown for 2 seconds after which the next memory trial automatically started. This was done to make the experiment virtually identical to the upcoming fMRI experiment.

Retention Interval Processing Phase. Participants had 2000 ms to respond to both stimuli. Two different retention intervals were used, 9 trials (22.5 seconds) and 11 trials (27.5 seconds) in which participants performed either one of the single tasks (tone or colour) or one of the dual-tasks (tone -> colour or colour -> tone). One trial lasted 2500 ms and for the dual-task the SOA was always 0 ms.

Procedure. There was only one memory load (6 letters) and two different types of task (single and dual-task). Each participant performed 40 memory trials in total (20 with a retention interval of 9 trials and 20 with 11 trials) equally divided between single (visual and auditory) and dual-task (tone -> colour and colour -> tone). The main experiment lasted about 35 min and before this the participants practiced all tasks for approx. 15 min.

6.1.2 Results

Since this was a pilot with seven participants, no outlier analysis was performed. The single task condition is the average of the single auditory task and the single visual task and the dual-task condition is the average of both response order conditions (tone -> colour and colour -> tone).

6.1.2.1 Recall performance

To test whether the processing task had an effect on memory recall, the relative recall between the single and dual-task processing task conditions for the two durations of retention interval (9 and 11 trials) was compared. A 2x2 repeated-measures ANOVA with factors processing task (single, dual-task) and length of retention interval (9 vs 11 trials) was conducted to test this. The main effect of processing task was not significant ($F(1, 6) = 5.85$, $p = 0.052$. However, for the retention interval of 11 trials, the relative recall was significantly higher in the single task (0.67 ± 0.29) compared to the dual-task (0.53 ± 0.28) ($t(6) = 2.45$, $p < 0.05$. For the retention interval of 9 trials, the relative recall was numerically larger in the single task condition (0.63 ± 0.29) compared to the dual-task condition (0.55 ± 0.25) but failed to reach significance ($t(6) = 1.91$, $p = 0.11$) probably due to low sample size (Figure 6.1). The main effect of length of retention interval was not significant ($F(1, 6) = 0.08$, $p = 0.79$) indicating that the difference in recall performance between the different retention interval durations was not significant. Processing task and length of retention interval did not interact ($F(1, 6) = 1.57$, $p = 0.26$). Hence, the results indicated that prolonging the retention interval from five trials to 9 or 11 trials still showed the effect of task processing on recall performance. Taking considerations of the MRI scanning procedure into account, it was decided to use 10 trials in the retention interval in the fMRI experiment.

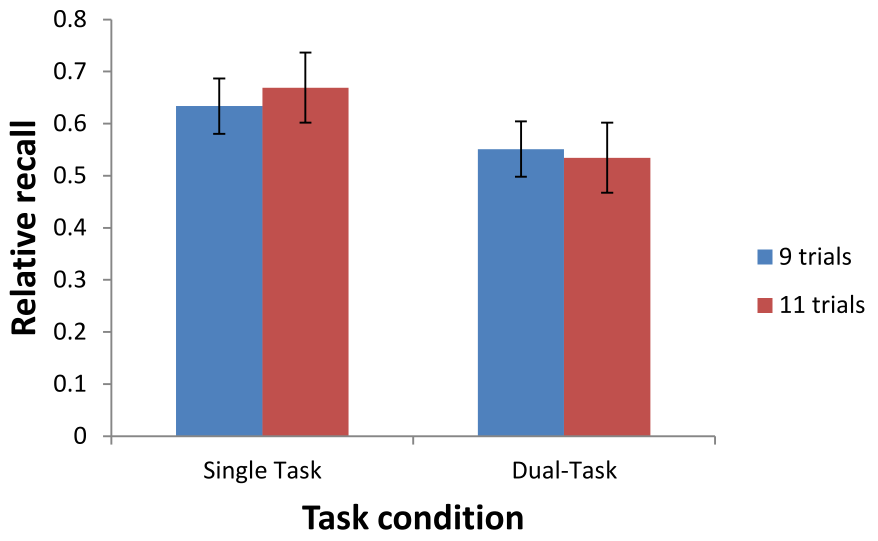


Figure 6.1: Relative recall performance for processing tasks of experiment 4a, the behavioural pilot of fMRI 1. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

6.1.2.2 Processing Task performance

Processing task performance measured by response times and error rates were not relevant for this pilot and therefore not reported in detail. However they generally showed the same pattern as in experiment 1b.

6.1.3 Discussion

This pilot study has shown that prolonging the retention interval does not change the effect of processing task on recall performance. Participants showed lower recall performance after performing a dual-task in the retention interval compared to a single task. This effect was shown for a retention interval of 9 trials (numerically different, not statistically) and a retention interval of 11 trials (significant difference). When taking optimum block length in an fMRI design into account, it was decided to use 10 trials in the retention interval in the fMRI study.

6.2 Experiment 4b: fMRI study 1

Experiment 4a, the pilot study, showed that prolonging the retention interval by increasing the number of trials did not change the effects in recall performance. Participants still remembered fewer letters when performing a dual-task in the retention interval as compared to a single task.

The next study used fMRI to determine whether PRP dual-task and WM activate the same brain areas. If they do, we take that as support for the idea that they rely on the same mental mechanisms. This can be broken down into three sub-questions. First, which activation patterns for executive functions occur in the brain to control the dual-task processes in the PRP paradigm? Secondly, what are the activation patterns in the brain for the executive functions of WM? And finally, are these two activation patterns the same? This study investigated how the neuroanatomical correlates of the two tasks compare to each other.

6.2.1 Method

6.2.1.1 Participants

Twenty-three (13 female) participants (mean age: 25 years, SD = 5.6, range 19-37 years) took part in the study after having given written informed consent. The study was approved by Brunel University's College of Health and Life Sciences Ethics Committee and participants received £20 for participation. The information leaflet for both MRI and the experiment, consent form for both MRI and the experiment, initial and second screening form for MRI, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 6.

6.2.1.2 Tasks

The tasks were similar to the behavioural pilot (experiment 4a) described above. The experiment again consisted of a WM span task with preload procedure which consisted of the following phases: cue, memory encoding phase, retention interval processing phase (single or dual-task), recall phase and feedback. This time also trials were used without the memory component, i.e. processing tasks only, so participants performed either a single or dual-task. Some adaptations were made for data acquisition in the scanner and hence for completeness all phases are described below. These tasks were performed block-wise. While lying in the fMRI scanner, the participants viewed a projection screen via a mirror. They responded on two separate fMRI-suitable button boxes, each with 5 keys.

Cue. The cue was displayed for 4 seconds and informed the participant about the upcoming trial, for instance "6 letters – Colour Only", or "Tone Only". Participants had to pay attention to the cue since it would indicate whether the upcoming trial would involve the memory component or not.

Memory Encoding Phase. This component was exactly the same as in the previous experiments. Only one memory load of 6 letters was used.

Retention Interval Processing Phase. This lasted 24.5 seconds for both the "memory + processing task" trials and the "processing tasks only" trials during which the participants performed one of the four processing tasks, i.e. auditory single task, visual single task, dual-task tone -> colour or dual-task colour -> tone. Participants had 2000 ms to respond to the stimuli on each trial. One trial lasted 2450 ms and for the dual-task the SOA was always 0 ms. Again participants got feedback on each trial whether the response was correct, error, wrong order (for dual-task) or too slow when not responding in time.

Recall Phase. This component changed compared to the behavioural experiments. Participants still had to recall the memorized letters in the order in which they were presented, but this time they did not use a keyboard for recall due to the MRI incompatibility. Instead, for each of the six letters that had to be remembered, one by one, a row of five letters was presented on the screen with the correct letter randomly placed among non-target letters. Participants had 3000 ms to indicate which letter was the one they had to remember by pressing the corresponding button on the button-box. After that a new row of five letters was presented with the 2nd correct letter of the remembered sequence randomly placed amongst non-target letters and again participants had to indicate which letter they had to remember. This was repeated 6 times in order to give a response for each of the 6 memorized letters. In the MRI practice participants practiced outside the scanner this recall procedure 10 times before moving on to the practice of the dual- tasks and the memory trials.

Feedback. This was exactly the same as in previous experiments. At the end of each ("memory + processing task" or "processing task only") trial participants received feedback on their performance in the retention interval. This was displayed for 1700 ms after which automatically the next trial started.

Processing tasks.

Auditory Single Task. A trial of the auditory single task started with a fixation cross displayed in the centre of the screen for 200 ms. Then randomly either a low (400Hz) or high (1000 Hz) pitched tone was presented for 100 ms via headphones. When the low pitched tone was presented, participants had to use the button below their left middle finger and when the high pitched sound was presented they had to press the button below their left index finger. From its onset, participants had 2000 ms to respond to the stimulus. Feedback at each trial was shown in the centre of the screen for 250 ms. A processing task block (because these tasks were done without memory retention as well) consisted of 10 trials lasting 2450 ms each.

Visual Single Task. This component was similar to the auditory single task except for the following changes. After the 200 ms fixation cross, randomly a blue or yellow circle was presented on the screen for 250 ms. When a blue circle was shown, participants had to press the button below their right index finger and when the yellow circle was shown, they had to press the button below their right middle finger.

Dual-task. After the 200 ms fixation cross, randomly either a low or high pitched tone was presented and at the same time (SOA = 0 ms) either a blue or yellow circle was presented. At the beginning of each trial the cue had indicated whether the response would be "Tone -> Colour" or "Colour -> Tone" and participants pressed the same buttons as in the respective single tasks. The other parameters are the same as described in the single task conditions.

No Task. In the memory trials ("memory + processing task"), one of retention intervals was a "No task" condition in which participants did not perform a task but saw a fixation cross for the duration of 24.5 seconds. All they had to do was to memorize/remember the letters.

Procedure. The main experiment was divided into two fMRI runs, each containing 31 ("memory + processing task", "processing tasks only" and 3 "Resting") trials and lasting 24 min each. All were randomised, except that each session started and ended with a resting condition which was used as a baseline in which a fixation cross was shown for 24.5 seconds after the cue of 4 seconds. In between the two runs, the anatomical scan was conducted lasting for about 4 min.

These trials consisted of 16 different "memory + processing task" trials (4 single auditory task, 4 single visual task, 2 tone -> colour dual-task, 2 colour -> tone dual-task and 4 no task), 12 "processing task only" trials (4 single auditory task, 4 single visual task, 2 tone -> colour dual-task and 2 colour -> tone dual-task). Before performing the experiment in the scanner, participants practiced each of the tasks outside the scanner for approx. 30 min. In total the entire experiment lasted about 1 hour 45 min per participant (1 hour MRI scanning, 30 min practice and 15 min paperwork and explanations).

6.2.1.3 MRI Procedure

Imaging was carried out at CUBIC (http://www.cubic.rhul.ac.uk/) using a 3T scanner (Trio, Siemens, Erlangen, Germany) equipped with a 32-channel array head coil. Participants were supine on the scanner bed and cushions were used to reduce head motion. 35 axial slices (192 x 192 mm FOV, 64 x 64 matrix, 3 x 3 mm in plane-resolution, 3 mm thickness, no gap, interleaved slice acquisition) were acquired using a BOLD-sensitive gradient echo EPI sequence (TR 2.5s, TE 31 ms, 85 flip angle). High-resolution whole-brain images were acquired from each participant using a T1-weighted MPRAGE sequence (TR 1900 ms, TE 3.03 ms, 11 flip angle, 176 slices, 256 x 256 mm FOV, 1 x 1 x 1 mm voxel size). Two functional runs with 583 volumes each were acquired each lasting 24 min. The sounds were tested through the headphones to confirm that they worked properly just before the scanning began. The participants were encouraged to keep as still as possible while they were in the scanner.

6.2.1.4 MRI Data Analysis

MRI data was analysed using SPM 12 (The FIL Methods group, 2017). The data was imported using DICOM import and converted to NifTi (nii) files. First the data was pre-processed which consisted of the following steps. First, the origin of the structural as well as functional images was manually aligned with the anterior commissure and the images were reoriented with pitch, roll and yaw if necessary. Next, head motion of all functional images was corrected (Realign & Unwarp). We checked for excessive movement by visual inspection of the movement output graphs. Third, functional and structural images were coregistered to maximise the mutual information which was checked by visual inspection for each subject. Fourth, the structural image was segmented based on tissue classification and the forward deformation field image was saved. After this, structural and functional images were both normalized to MNI space using a voxel size of 2 x 2 x 2 mm^3 for the functional images and a voxel size of 1 x 1 x 1 mm^3 for the structural image by using the deformation field saved in the previous step. After both normalisations, a functional normalized image, the structural normalised image and a template image were visually inspected to ensure normalisation success. Finally, functional data were spatially smoothed using a Gaussian kernel with a FWHM of 8 mm. The next steps of the data analysis are the first level (on a subject basis) and second level (on a group level) statistics.

Statistical analysis was based on a voxel-wise least-squares estimation using the general linear model (Friston et al., 1995). Because the current study used a blocked fMRI design, a boxcar function, convolved with a canonical HRF without derivatives, was used to model the BOLD response. Eight conditions were used to calculate contrasts of interest (Table 6.1). For the first level statistics, the encoding, processing and recall phases were all modelled by separate regressors, but for the remaining part of the analyses only the task processing period (i.e. retention interval) is of relevance. In the terminology of the condition names, the addition of “M” means that the memory component was added to create a complex WM task, otherwise it was just a processing task without any memory component. DT is the average of DTav (first respond to auditory then visual stimulus) and DTva (first respond to visual then auditory stimulus), the same holds true for MDT (average of MDTav and MDTva). A temporal high-pass filter with a cut-off frequency of 1/430 Hz was applied. Individual contrast maps were calculated for all contrasts of interests (see “Results” section) and the second-level analysis was based on one-sample t-tests. All resulting t-maps were thresholded at $p < 0.05$ (FWE corrected) and if no significant clusters were found, $p < 0.001$ (uncorrected) was considered.

Also, always a cluster threshold of 0 voxels was used. Anatomical locations were determined using the Automated Anatomical Labeling toolbox (Tzourio-Mazoyer et al., 2002).

Table 6.1: Conditions used in Experiment 4b.

AUD	Auditory Single Task
MAUD	Auditory Single Task with Memory task
VIS	Visual Single Task
MVIS	Visual Single Task with Memory Task
MST	One of the single tasks with Memory Task
DT	Dual-Task
MDT	Dual-Task with Memory Task
M	No processing task in the retention interval, just remembering the letters

To test for dual-task specific activation, i.e. activations specific to the dual-task which cannot be explained by the single tasks, the contrast DT - AUD - VIS [1 -1 -1] was calculated leading to PRP-specific activations (Szameitat et al., 2011). Secondly, to identify WM-specific activations, i.e. activations specific to the combination of the processing task and the memory task, the contrast MST – M – ST [1 -1 -1] was calculated which will lead to WM specific activations. When comparing the results of the first and second contrast to see whether the two activation patters are the same, the assumption is that involvement of the same areas is indicative of the same underlying processes (executive functions) and that involvement of different areas would reflect different underlying processes.

6.2.2 Results

Due to excessive head movement, two subjects were excluded from the analysis. All other participants had behavioural data within 3 standard deviations of the mean, so no further participants were excluded. Due to a technical mistake, in some participants the superior part of the brain was not recorded, so that also in the group average these parts are missing.

6.2.2.1 Behavioural results

6.2.2.1.1 Recall performance

To test whether the processing task had an effect on memory recall, we compared the relative recall between the three types of processing tasks (single task, dual-task or no task) by conducting a one-way repeated-measures ANOVA. Mauchly's test indicated that the assumption of sphericity had not been violated. Results showed that the processing task had an effect on memory recall ($F(2,40) = 18.00$, $p < 0.001$). Follow-up pairwise t-tests showed that relative recall performance for all task conditions significantly differed from each other (all $t(20) > 2.22$, $p < 0.04$). Recall performance was largest in the no task condition (0.77 ± 0.23), followed by single task (0.71 ± 0.24) and was lowest after performing the dual-task condition in the retention interval (0.58 ± 0.28) (Figure 6.2). This indicates that dual-task performance relies at least partially on the same cognitive processes as WM.

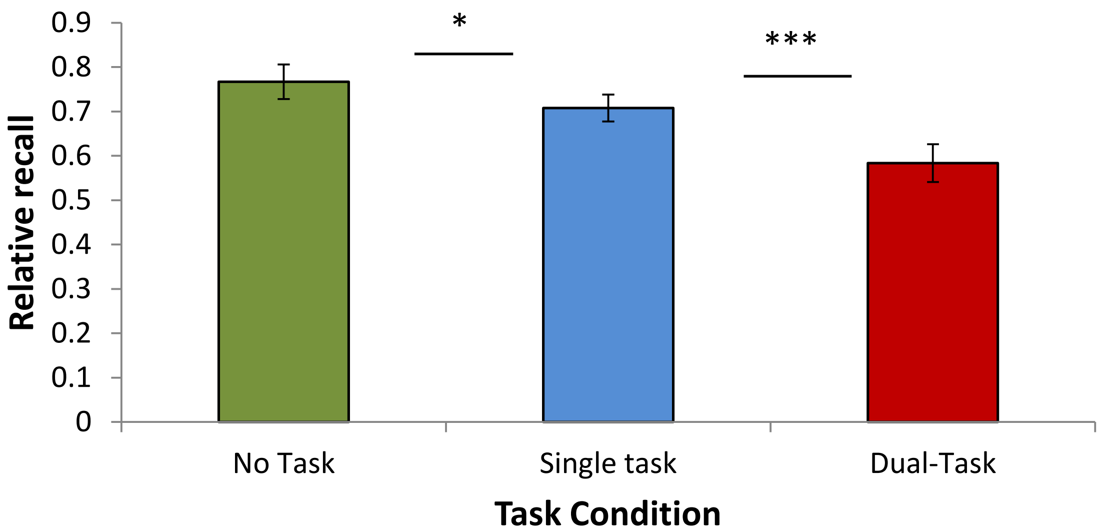


Figure 6.2: Relative recall performance for the three different processing tasks (no task, single task and dual-task) of Experiment 4b. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**. Results of paired samples t-tests testing for recall performance differences are shown (* p < 0.05), (*** p < 0.001).**

6.2.2.1.2 Processing Task performance

Performance on the processing task was again analysed in terms of response times and error rates. For these analyses, the performance on "memory + processing tasks" and "processing task only" trials is reported separately.

Response times. Participants responded faster in the "processing task only" trials as compared to the "memory + processing task" trials. Single task RT1s of the "memory + processing task" trials (563 ± 73 ms) were significantly longer than the single task RT1s of the "processing task only" trials (524 ± 71 ms) ($t(20) = 3.18$, $p = 0.005$). RT1s of the dual-task of the "memory + processing task" trials (881 ± 125 ms) were also significantly longer than the RT1s of the dual-task of the "processing task only" trials (855 ± 109 ms) (t(20) = 2.14, p = 0.045). Dual-task RT2s of the "memory + processing task" trials (1142 ± 128 ms) were not significantly different from the RT2 of the "processing task only" trials (1138 ± 130 ms) (t(20) = 0.36, p = 0.72) (Table 6.2, Figure 6.3).

Table 6.2: Response times in ms and errors in percentages of the different task conditions of Experiment 4b split by type of trial, "memory plus processing task" trials and "processing task only" trials.

Variable	**RT in ms**				**Error rate in %**	
Processing Task	RT1		RT2			
	Memory + Processing Task	Processing Task Only	Memory + Processing Task	Processing Task Only	Memory + Processing Task	Processing Task Only
Single Task Visual	510 ± 73	483 ± 97	-	-	2.68 ± 2.21	2.44 ± 2.42
Single Task Auditory	616 ± 92	564 ± 70	-	-	4.40 ± 6.07	3.10 ± 5.06
Dual-Task (Tone -> Colour)	940 ± 123	892 ± 111	1153 ± 122	1138 ± 114	15.48 ± 11.20	11.90 ± 9.65
Dual-Task (Colour -> Tone)	825 ± 151	820 ± 132	1134 ± 154	1141 ± 177	15.12 ± 8.12	13.45 ± 10.85

Errors. The error rates of the "memory + processing task" trials (ST: 3.54 ± 3.13, DT: 15.30 ± 8.58) were numerically larger than the error rates of the "processing task only" trials (ST: 2.78 ± 2.50, DT: 12.68 ± 9.59), but failed to reach significance (all t(20) < 1.87, p > 0.076). Overall, participants made significantly more errors in the dual-task condition (13.99 ± 8.05 %) compared to the single task condition (3.15 ± 2.67 %) (t(20) = 7.52, p < 0.001) (Figure 6.3). Error rates in dual-task condition were also significantly higher than error rates in the single task conditions when looking at the "memory plus processing task" trials and the "processing task only" trials separately (all t(20) > 5.45, p < 0.001). Overall, errors rates were not very high (all averages below 20%) which indicates that participants focused on their performance in the processing task.

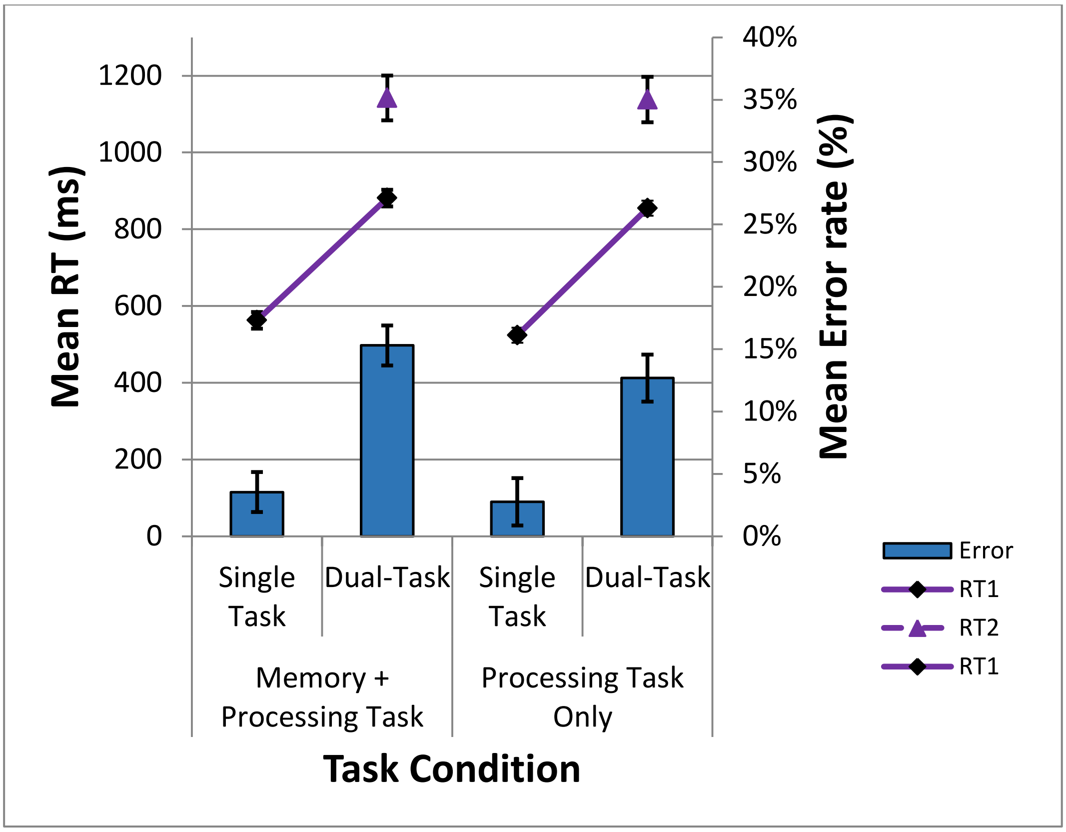


Figure 6.3: Mean response times (left axis, lines) and error rates (right axis, bars) for each dual-task condition of experiment 4b. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

6.2.2.2 Neuroimaging results

The fMRI results are split into several sections. The goal of the present experiment was to determine whether the executive functions of a PRP dual-task are similar to the executive functions of WM. In other words, does a WM dual-task (the complex WM span task with one of the single tasks as the processing task) activate the same areas as the PRP dual-task? This was analysed using the method of cognitive subtraction. As mentioned earlier, we conducted an interaction analysis composed of the following contrasts: (DT – AUD – VIS) and (MST – ST – M) where ST is (AUD + VIS)/2. The contrast (MST – ST – M) was chosen because the MST condition is also a dual-task consisting of one memory task and one single task which is similar to a dual-task in the PRP paradigm consisting of two processing tasks. We did choose MST and not MDT, because one could say that the MDT condition consists of three tasks (one memory task and two processing tasks to perform) and not two tasks. Another reason for the chosen contrast is that the condition MT measured by the contrast (MDT – DT – M) is very difficult and may result in ceiling effects in the BOLD activation (cf. (Barch et al., 1997). Finally, the MDT contrast and the PRP contrast are relatively dependent of one another since the MDT contrast consists of the memory component and the PRP dual-task, i.e. MDT can be seen as MPRP. Therefore, MST and PRP are more independent from one another than MDT and PRP.

The contrasts will show overadditive activation, i.e. PRP specific for (DT – AUD – VIS) showing overadditive effects which are dual-task specific and WM specific for (MST – ST – M) and we believe this activation reflects the executive functions in these two tasks. The (DT – AUD – VIS) contrast shows the executive functions involved in the PRP dual-task (left panel of Figure 6.4), whilst the (MST – ST – M) contrast shows the executive functions in WM (right panel of Figure 6.4). This figure shows brain activations and our interpretation is that those activations reflect executive functions. In all analyses we focused on prefrontal areas. Seventeen (absolute and local) activated peaks were found in the (DT – AUD – VIS) contrast whilst eight activated peaks were found in the (MST – ST – M) contrast. Both contrasts resulted in extensive activation of lateral and medial PFC.

The PRP contrasts resulted in activations of the MFG in both hemispheres, (BA 46, 10, 6). Also, the IFJ was activated in both hemispheres (BA 9, 6). In the right hemisphere there were furthermore activations in the SFG (BA 9, 6) and the precentral sulcus (BA 6). In the left hemisphere there were furthermore activations in SFS (BA 6), IFG (BA 44, 9) and pre-SMA (BA 6).

The WM contrast did not result in any bilateral activations. In the right hemisphere there were activations in MFG (BA 9, 46) and pre-SMA (BA 6). In the left hemisphere there were activations in SFS (BA 6), IFJ (BA 9) and ACC (BA 24).

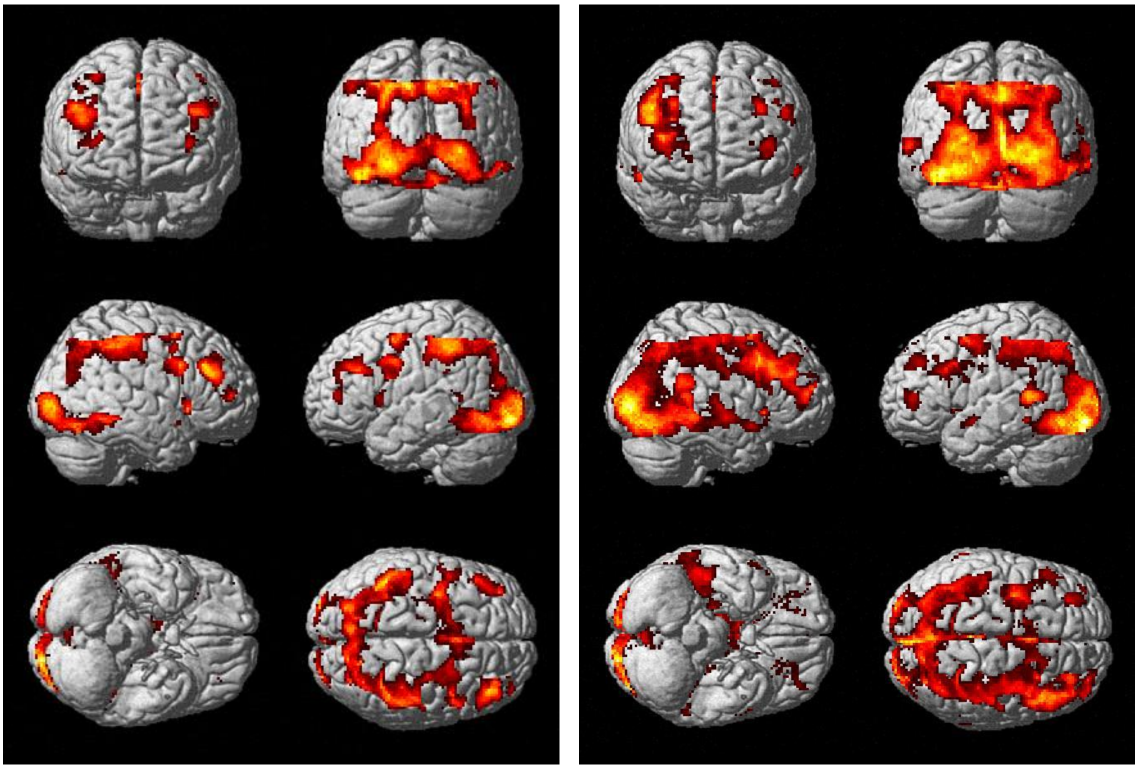


Figure 6.4: Activations in the PRP dual-task (contrast DT – AUD – VIS, left panel) and in the working memory task (contrast MST – ST – M, right panel). For illustration purposes, the left panel is thresholded at $p < 0.05$ (FWE) and the right panel is thresholded at $p < 0.00005$ uncorrected.

On closer inspection, it turned out that many of the coordinates of the PRP and WM contrasts were virtually identical. To simplify the dataset these redundant peak coordinates were removed and if two activation peaks were in proximity in terms of Euclidean distance of 10 mm or less and they were localized in the same gross anatomical structure, they were considered to be the same and only one coordinate was used (i.e. the one with the highest t-value). It turned out that 14 activation peaks in both contrasts were identified as similar which reduced the number of peaks from 25 to 19 (Table 6.3).

Table 6.3: MNI coordinates of the 19 clusters that showed activation in either the PRP dual-task contrast or the WM contrast or both. Note: Abbreviation of the area names: IFG = inferior frontal gyrus, MFG = middle frontal gyrus, SFG = superior frontal gyrus, SMA = supplementary motor area, IFJ = inferior frontal junction, ACC = anterior cingulate cortex, SFS = superior frontal sulcus.

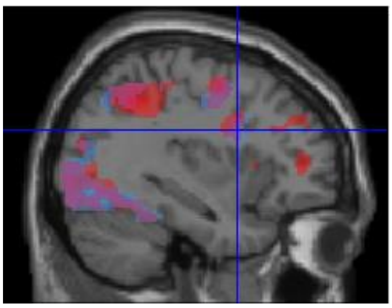
Peak	Area	BA area	(x,y,z) coordinate	t-value	p-value (FWE)	z-value
Right hemisphere						
1	rMFG	BA 46	(38,54,8)	7.67	0.006	5.18
2	rSFG	BA 9	(44,34,34)	11.20	< 0.001	6.23
3	rMFG	BA 46	(48,28,28)	7.54	0.007	5.13
4	rMFG	BA 9	(38,14,30)	9.28	< 0.001	5.71
5	rSFG	BA 6	(4,10,54)	10.17	< 0.001	5.97
6	Precentral sulcus	BA 6	(40,6,44)	8.62	0.001	5.51
7	rPre-SMA	BA 6	(6,6,50)	9.40	< 0.001	5.75
8	rIFJ	BA 9	(42,4,30)	10.76	< 0.001	6.12
Left hemisphere						
9	lMFG	BA 46/10	(-34,44,6)	10.07	< 0.001	5.94
10	lMFG	BA 46	(-40,36,32)	9.48	< 0.001	5.77
11	lIFG	BA 44	(-52,14,4)	8.40	0.002	5.44
12	lPre-SMA	BA 6	(-6,8,52)	11.30	< 0.001	6.26

13	lIFJ	BA 9	(-30,6,32)	12.10	< 0.001	6.44
14	lIFJ	BA 9	(-32,6,26)	9.74	< 0.001	5.85
15	lIFG	BA 9	(-44,2,34)	10.88	< 0.001	6.15
16	ACC	BA 24	(-8,2,48)	9.25	< 0.001	5.71
17	lMFG	BA 6	(-28,-4,56)	15.09	< 0.001	7.02
18	lSFS	BA 6	(-32,-4,46)	10.14	< 0.001	5.96
19	lSFS	BA 6	(-22,-10,50)	12.30	< 0.001	6.49

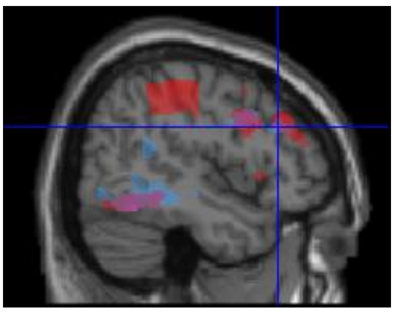
The fMRI results showed considerable overlap as well as some differentiation in brain activation for the PRP and the WM tasks. In more detail, both areas activated the IFJ, i.e. the area surrounding the junction of the inferior frontal sulcus (IFS) and the precentral sulcus, the middle frontal gyrus (MFG) and the pre-supplementary motor area (pre-SMA) in both hemispheres, the right super frontal gyrus (SFG), the left anterior cingulate cortex (ACC) and the left superior frontal sulcus (SFS) (Figure 6.5)Figure 6.5. With respect to differentiation, the PRP task activated more the right inferior MFG whilst the WM component activated more the left superior MFG.

It might seem of interest to calculate the direct comparison (DT – AUD – VIS) – (MST – ST – M). This contrast would show differences in relative activation strength. However, in our case, these differences are not necessarily informative because the two tasks are not matched for their difficulties. Also, the primary interest is similarities in patterns of overlap between (DT – AUD – VIS) and (MST – ST – M). A more appropriate approach would be to look at where the activation patterns overlap, i.e. a conjunction analysis. A visual representation of the overlapping areas is given in Figure 6.5. In order to provide further evidence that both tasks demand the same processes, subsequent analyses were conducted.

Left IFJ



Right MFG



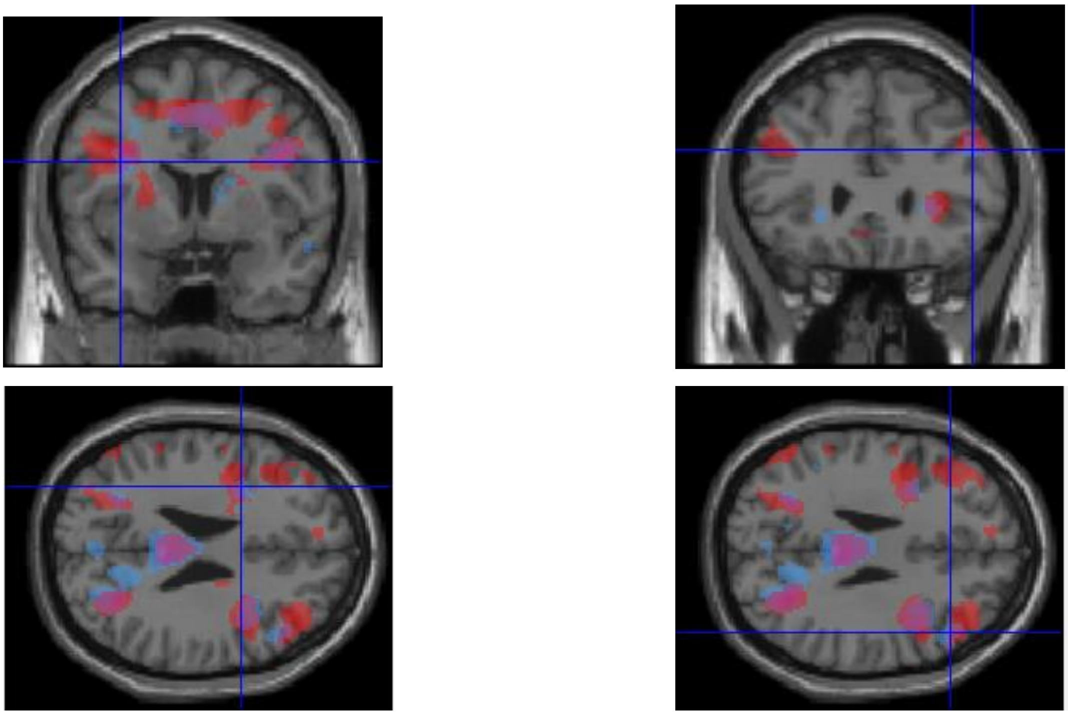
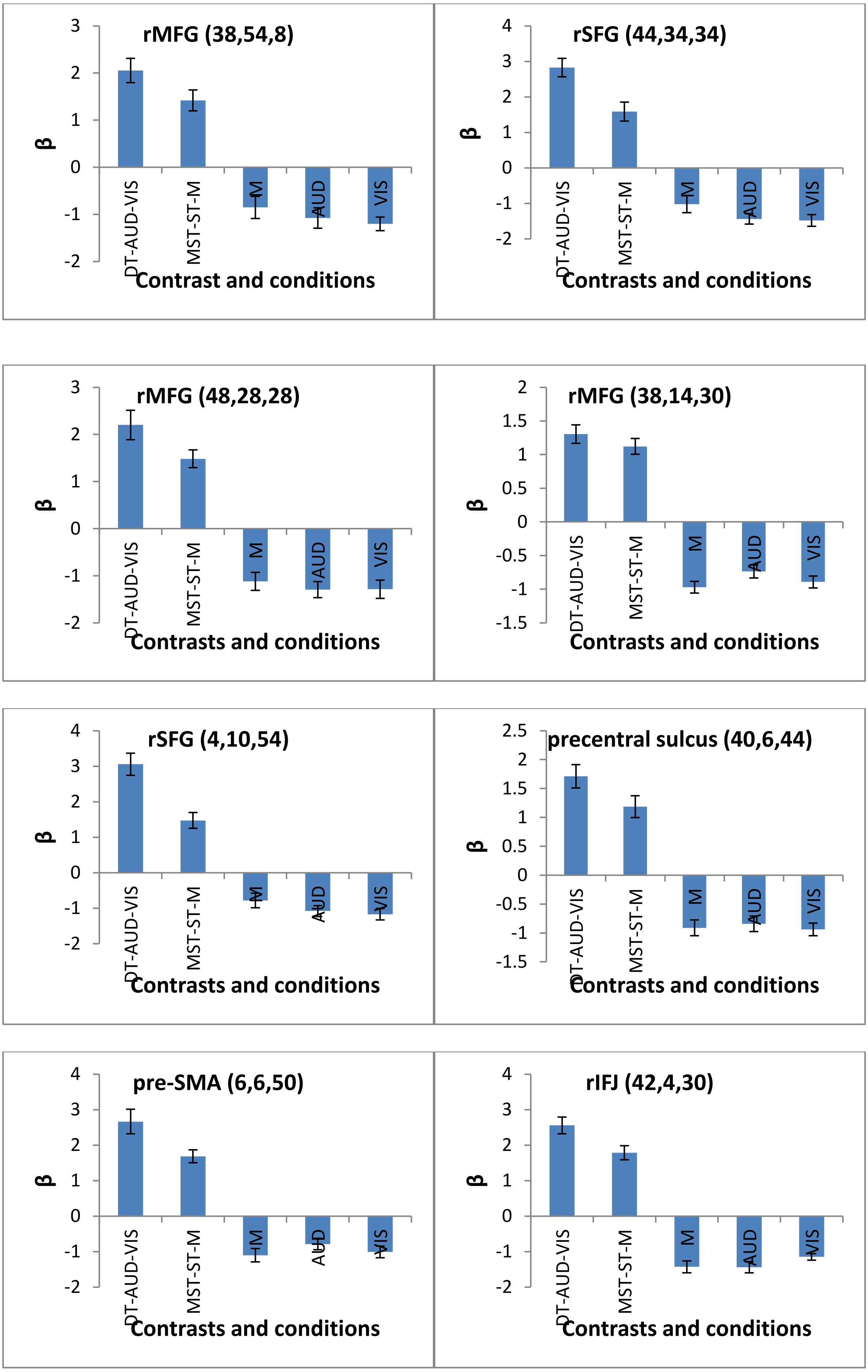
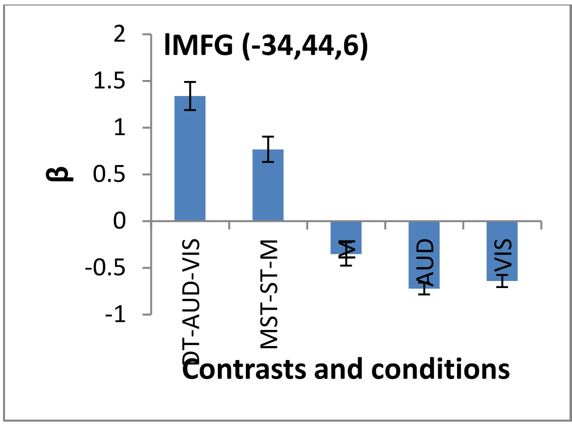
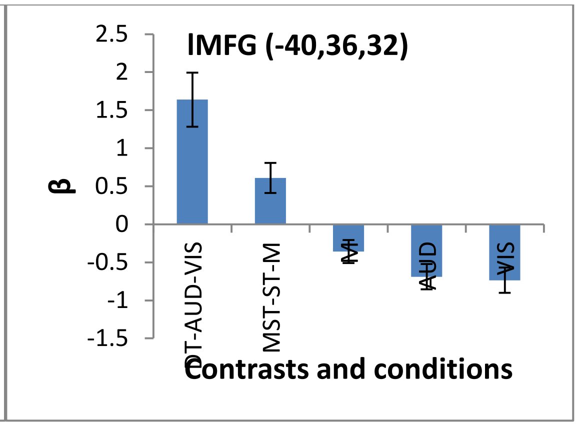


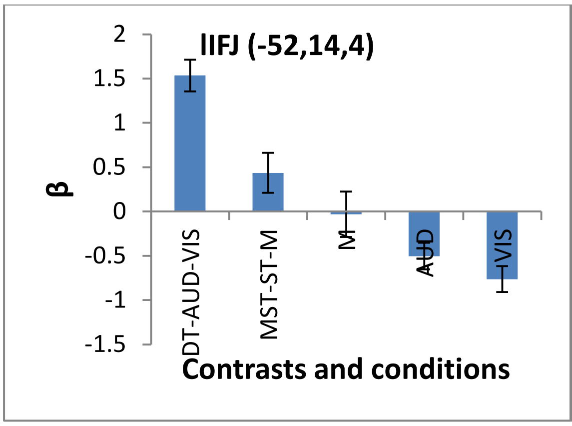
Figure 6.5: Overlap in brain activation of the PRP (DT – AUD – VIS) and the WM (MST – ST – M) contrast. The brain activation in red shows the activation in the PRP contrast whilst the brain activation in blue shows the activation in the WM contrast. The brain activation in purple shows the overlap in activation of the two contrasts, mainly in the left IFJ (-33,5,25) as is shown on the left and in the right MFG (48,27,27) as is shown on the right.

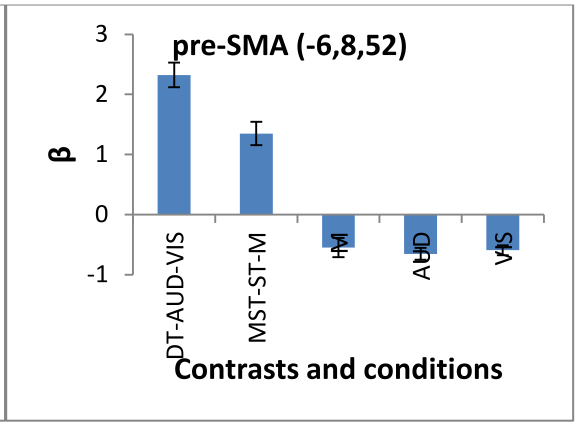
Patterns. For these nineteen peaks, the next step was to look at the brain activation in the different conditions to find out whether an area that was active in the PRP contrast was also active in the WM contrast. For this, the beta values (the MRI parameter estimates) for the different conditions and the two contrasts (PRP and WM) were displayed (Figure 6.6). The beta values were derived from the respective contrasts for PRP (DT – AUD – VIS) and WM (MST – ST – M) of individual maps. This was done to show that PRP-areas also show activity during WM and vice versa. The conditions (M, AUD and VIS) were added for information but are not relevant for the point we want to make. Beta values of both the PRP contrast (DT-AUD-VIS) and the WM contrast (MST-ST-M) are similar in height for all clusters. This illustrates that an area which is identified in PRP is also activated in WM and vice versa. For all clusters, the beta values for both the interaction contrasts (DT – AUD – VIS) and (MST – ST – M) were larger than the beta values for their individual conditions (M, AUD, VIS). This shows that there is over-additive activation present to process the dual-task or the WM task as compared to the single tasks, which we propose is associated with executive functions. One sample t-tests showed that for all clusters of both contrasts the beta values were significantly different from zero (all $t(20) > 6.61$, $p < 0.001$). This means that each regressor has a significant contribution to explain the observed data in that area. The beta values of the conditions (not the contrasts) are mostly negative. Presumably this is due to the way the beta values are calculated, because the absolute values are arbitrary and therefore only the relative heights of the bars to each other is of relevance.

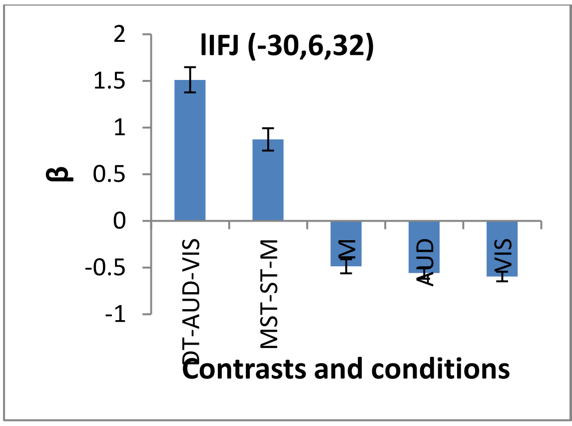

rMFG (38,54,8)
β
Contrast and conditions
DT-AUD-VIS
MST-ST-M
M
AUD
VIS
rSFG (44,34,34)
β
Contrasts and conditions
rMFG (48,28,28)
rMFG (38,14,30)
rSFG (4,10,54)
precentral sulcus (40,6,44)
pre-SMA (6,6,50)
rIFJ (42,4,30)

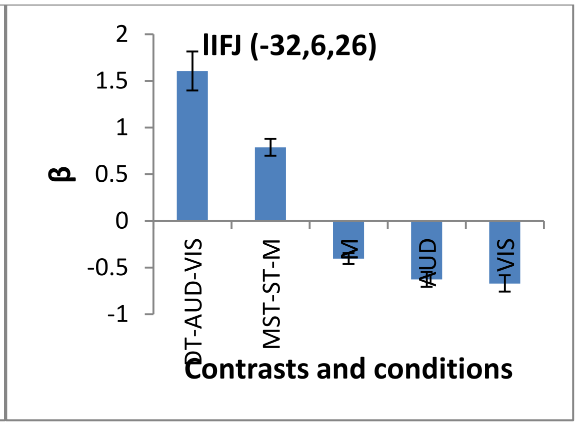

lMFG (-34,44,6)
β
DT-AUD-VIS
MST-ST-M
M
AUD
VIS
Contrasts and conditions

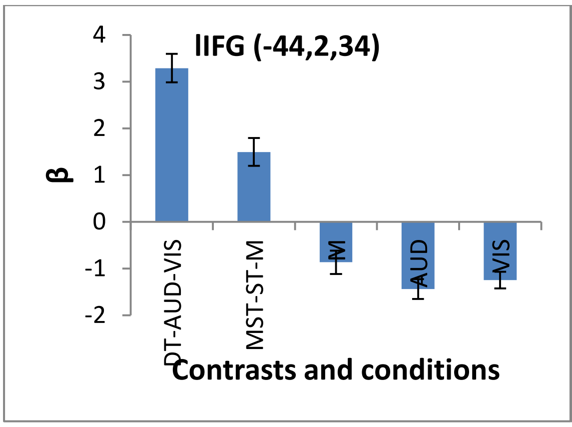

lMFG (-40,36,32)
β
DT-AUD-VIS
MST-ST-M
M
AUD
VIS
Contrasts and conditions

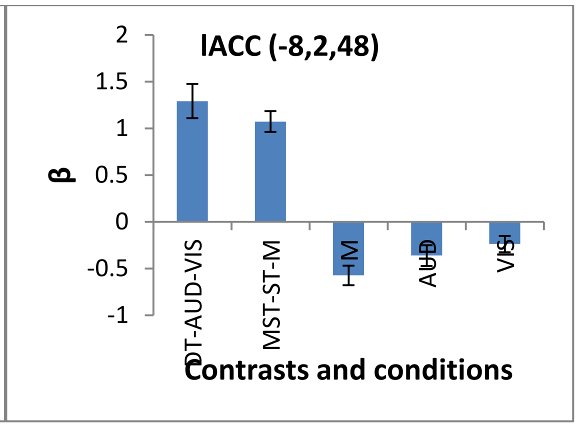

lIFJ (-52,14,4)
β
DT-AUD-VIS
MST-ST-M
M
AUD
VIS
Contrasts and conditions


pre-SMA (-6,8,52)
β
DT-AUD-VIS
MST-ST-M
M
AUD
VIS
Contrasts and conditions


lIFJ (-30,6,32)
β
DT-AUD-VIS
MST-ST-M
M
AUD
VIS
Contrasts and conditions


lIFJ (-32,6,26)
β
DT-AUD-VIS
MST-ST-M
M
AUD
VIS
Contrasts and conditions


lIFG (-44,2,34)
β
DT-AUD-VIS
MST-ST-M
M
AUD
VIS
Contrasts and conditions


lACC (-8,2,48)
β
DT-AUD-VIS
MST-ST-M
M
AUD
VIS
Contrasts and conditions

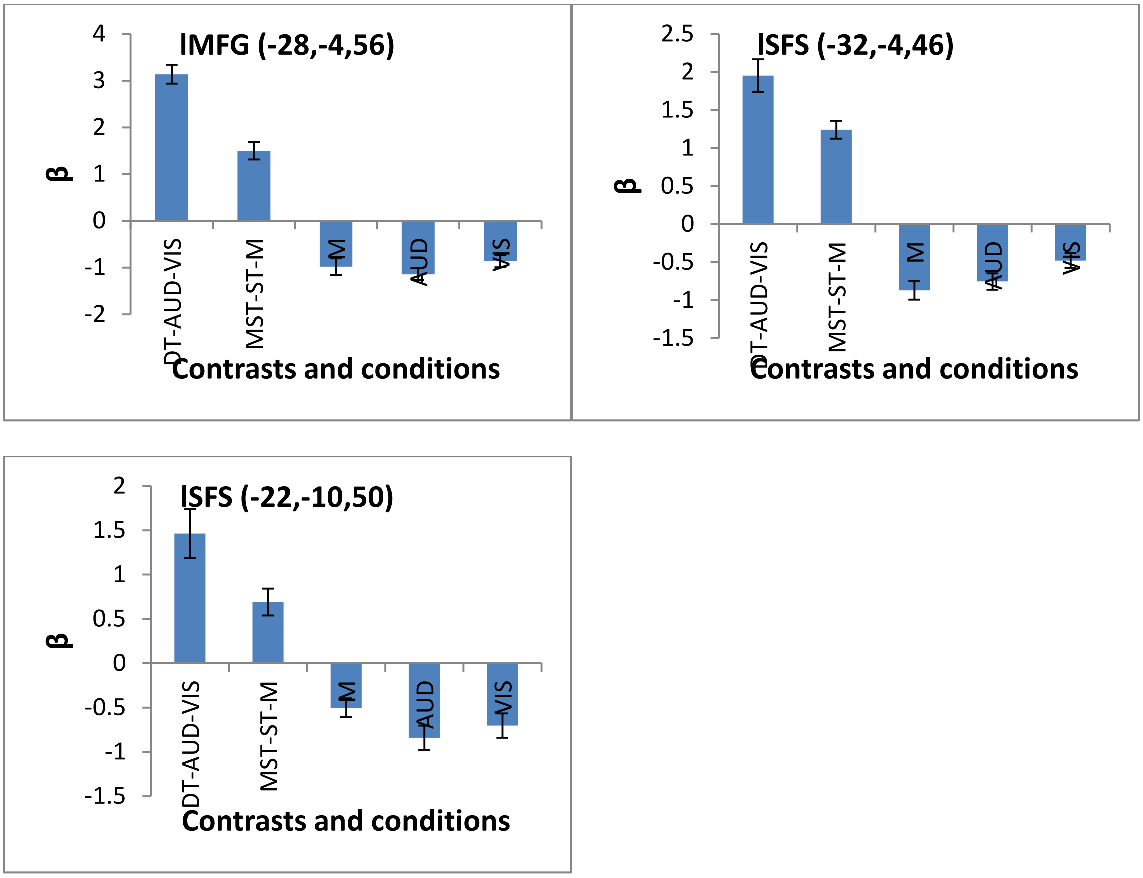


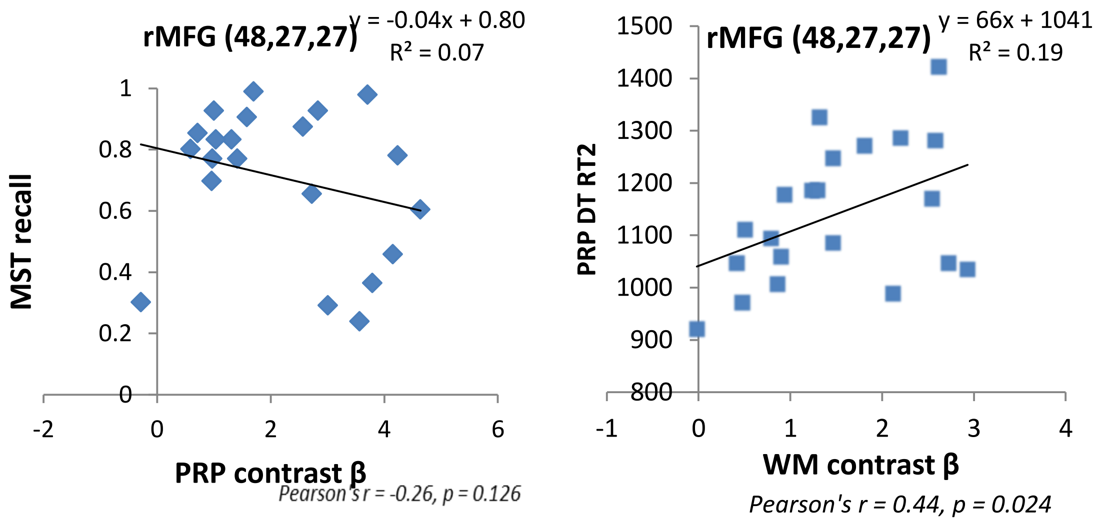
Figure 6.6: Brain activity β for the different contrasts and conditions shown for the nineteen different peaks.

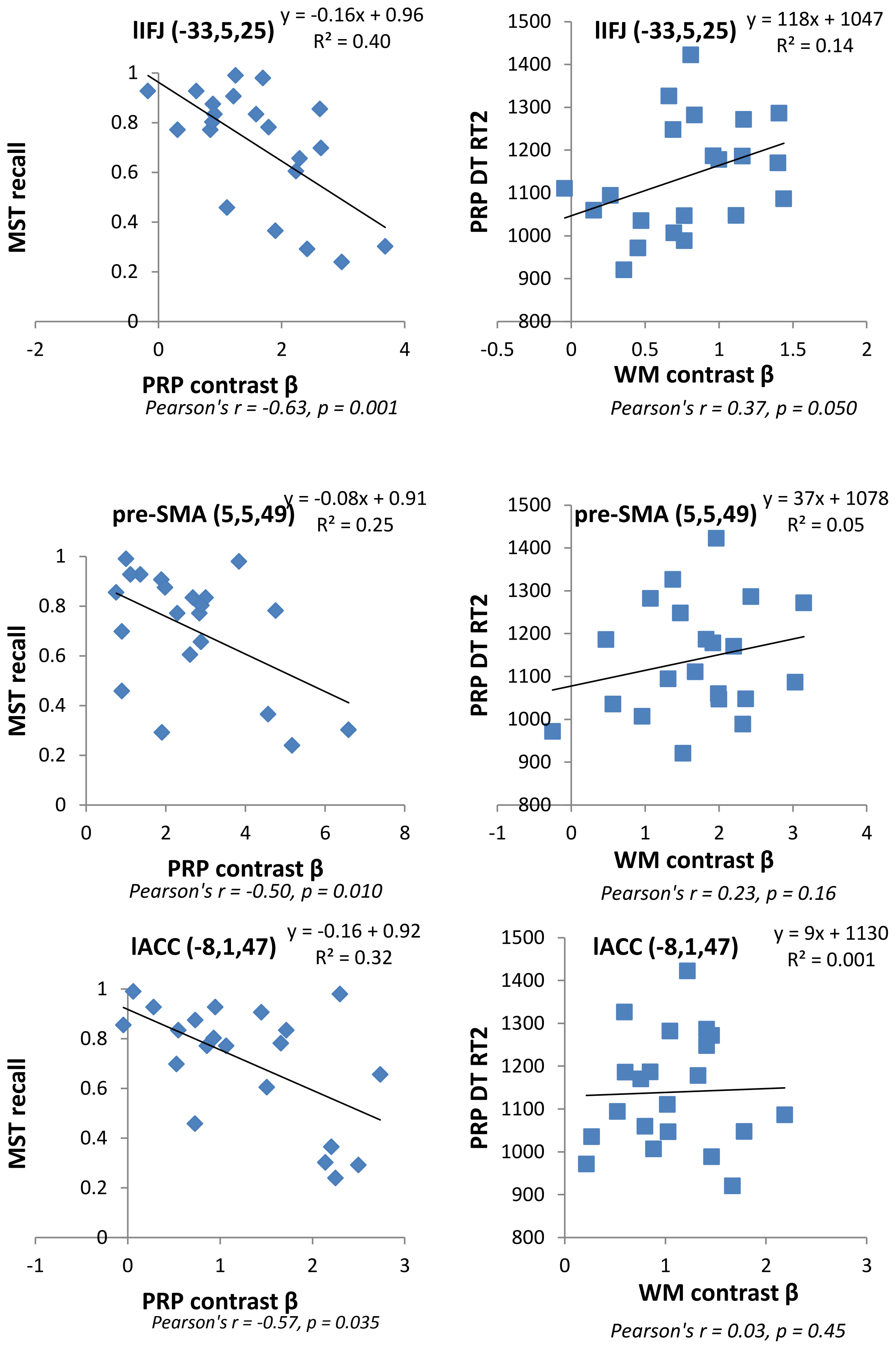
<u>Correlation analysis 1.</u> If the PRP and WM task are indeed related to each other by means of common demands on executive functions, then it should be possible to predict brain activation in one task with the behavioural performance in the other task. In other words, any area that subserves both tasks should show a correlation between the subject-individual beta values derived from the respective contrasts, i.e. (A) PRP (DT – AUD – VIS) and (B) WM (MST – ST – M), with the behavioural performance in the (A) WM task and (B) the PRP task, respectively. This leads to two correlations. One is the correlation between the beta values of the PRP contrast (called “PRP beta”) and the behavioural performance in the WM task, as measured by MST recall. The other one is the correlation between the beta values of the WM contrast (called “WM beta”) and the behavioural performance in the PRP task, as measured by RT2 in a pure PRP trial (condition DT, i.e. without the memory component). I chose RT2 because it is the most sensitive measure of PRP behavioural performance costs, since it captures any kind of deferment which can occur in task processing. Previous evidence from complex WM tasks (Smith et al., 2001) as well as other paradigms (Braver et al., 1997; Szameitat et al., 2016) suggest that in lateral prefrontal areas, lower performance is associated with higher brain activation, which is why we calculated one-tailed p-values for the Pearson’s correlation coefficients. Taken together, a negative correlation, i.e. decreasing performance is associated with increasing beta values, would support the idea that both PRP and WM support executive functions. Please note that in the PRP paradigm, decreasing performance is

associated with increasing RTs, which is why in that case a positive correlation coefficient indicates the above association, i.e. decreasing performance results in increasing beta values.

Because one might argue that areas which do not show this correlation across tasks might potentially not reflect common underlying executive functions, we from now on only focus on peaks which showed a significant correlation in at least one of the two correlations just described, which was the case for six out of the 19 peaks described above. However, for all further analyses the data of the remaining 13 peaks are shown in Appendix 7.

First, results of the correlation between the PRP beta values and the MST recall performance are reported. Overall, four peaks showed a negative significant correlation between the PRP beta values and the recall performance in the MST condition (all N = 21, Pearson's $r > -0.374$, $p < 0.048$). Two peaks which were significant in the other correlation (WM beta with RT2) also showed a negative correlation and almost reached significance ($p = 0.126$ and $p = 0.150$ (Figure 6.7 left panel). For the scatterplots of the correlation between brain activity in PRP and the recall performance in MST of the other 13 peaks, see Appendix 7A. To summarise, these 13 peaks mostly showed also a negative relationship (for all N = 21, Pearson's $r < 0.354$, $p > 0.058$). Taken together, these results show that indeed a negative relationship exists between the PRP beta values and the MST recall performance, supporting the hypothesis that both tasks are subserved/associated with the same executive functions.





lIFJ (-33,5,25)
y = -0.16x + 0.96
R² = 0.40
MST recall
PRP contrast β
Pearson's r = -0.63, p = 0.001
lIFJ (-33,5,25)
y = 118x + 1047
R² = 0.14
PRP DT RT2
WM contrast β
Pearson's r = 0.37, p = 0.050
pre-SMA (5,5,49)
y = -0.08x + 0.91
R² = 0.25
MST recall
PRP contrast β
Pearson's r = -0.50, p = 0.010
pre-SMA (5,5,49)
y = 37x + 1078
R² = 0.05
PRP DT RT2
WM contrast β
Pearson's r = 0.23, p = 0.16
lACC (-8,1,47)
y = -0.16 + 0.92
R² = 0.32
MST recall
PRP contrast β
Pearson's r = -0.57, p = 0.035
lACC (-8,1,47)
y = 9x + 1130
R² = 0.001
PRP DT RT2
WM contrast β
Pearson's r = 0.03, p = 0.45

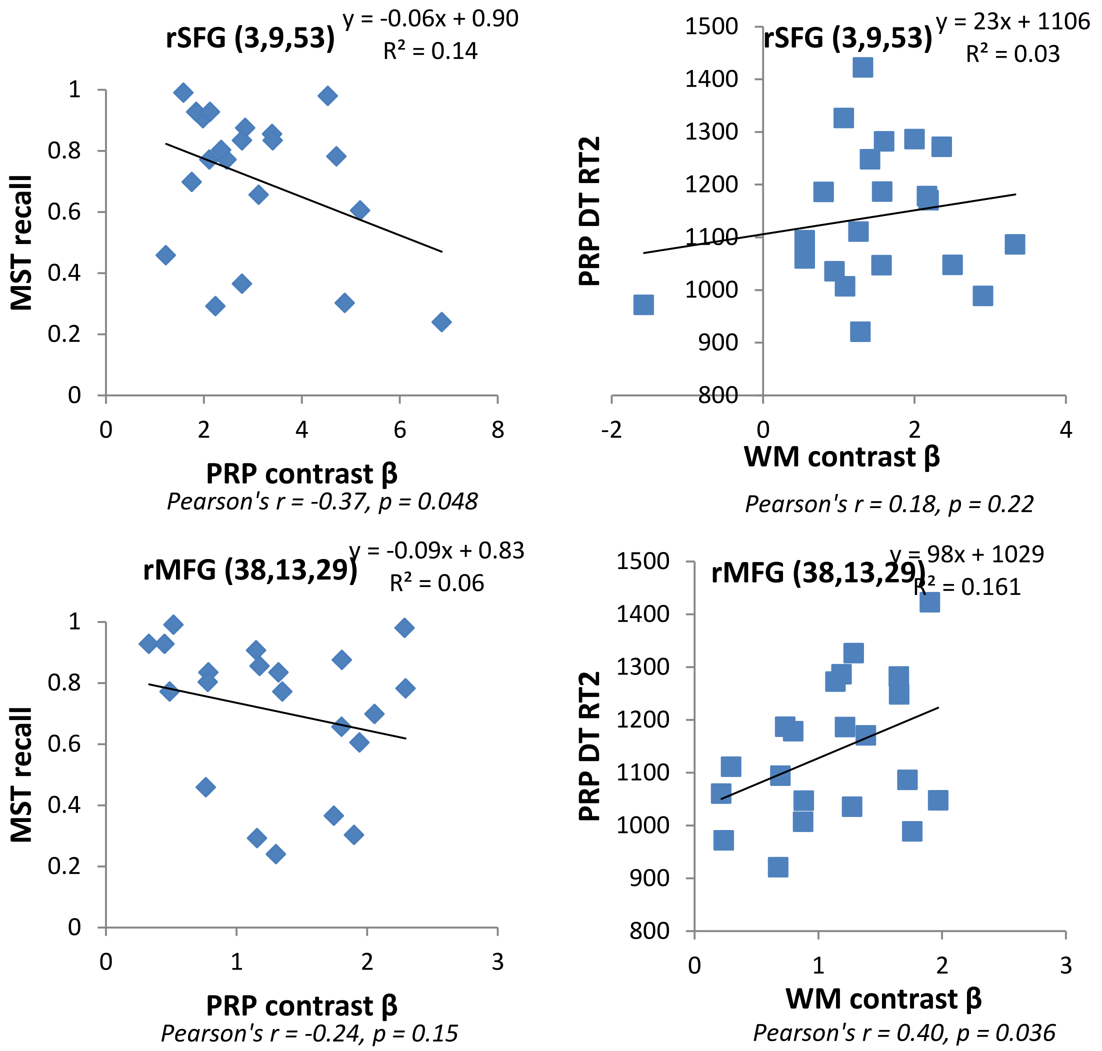
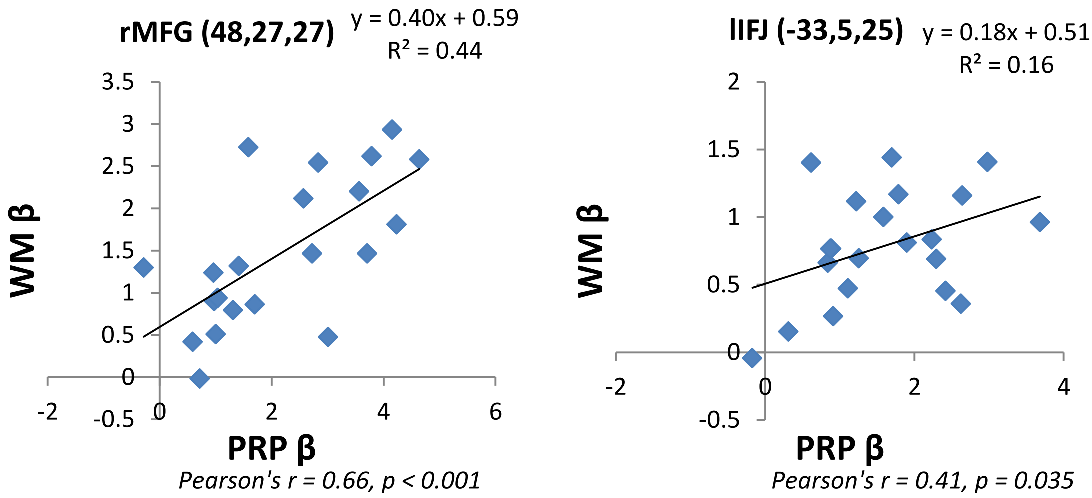


Figure 6.7: Scatterplot for each of the six different peaks showing the correlation between the brain activity in PRP and the behavioural performance in WM as measured by MST recall (see left panel). Scatterplot for each of the six different peaks showing the correlation between the brain activity in WM and the behavioural performance in PRP as measured by DT RT2 (see right panel). Note that in the PRP paradigm, decreasing performance is associated with increasing RTs, which is why in that case a positive correlation coefficient indicates the following association, i.e. decreasing performance results in increasing beta values.

Correlation analysis 2. Next, it was tested whether this relationship also holds true for the relationship between the WM beta value and the PRP behavioural performance. If executive functions of PRP and WM indeed overlap, one would expect a negative correlation between the WM beta values and the PRP behavioural performance. In other words, when the brain activity increases for the WM task, people would become slower in the performance of the dual-task because attention needs to be shared between rehearsing the letters and performing the dual-task in the retention interval. For the PRP behavioural performance measure, we used the DT RT2 values as explained earlier. Because in the PRP task decreased performance is reflected by increased values (the worse participants perform, the higher RT2), we actually predicted a positive correlation here. Again, this relationship was tested using Pearson's correlations for each of the six peaks. Overall, three of the peaks showed a positive significant relationship between the WM beta values and the

RT2 of the dual-task (all N = 21, Pearson's r > 0.37, p < 0.05). One of the other three peaks also showed a positive relationship and almost reach significance (N = 21, r = 0.228, p = 0.16). Two of the peaks did not show a significant relationship (all N = 21, Pearson's r < 0.175, p > 0.22) (Figure 6.7 right panel). For the scatterplots of the correlation between brain activity in WM and DT RT2 performance of the other 13 peaks, see Appendix 7B where most of the peaks also show a positive relationship (for all N=21, Pearson's r < 0.350, p > 0.06).

<u>Correlation analysis 3.</u> A further indication that the PRP task and the WM task are related to each other and both require similar executive functions is that the beta values of both contrasts themselves should correlate with each other. To test this relationship, Pearson's correlations between the PRP beta values and the WM beta values were conducted. This would give us additional confirmation that when an area shows a certain amount of PRP-specific activation, it also shows a correlating amount of WM-specific activation. Overall, results showed that there was a positive, significant relationship between the beta values of the PRP contrast and the beta values of the WM contrast for 5 of the 6 peaks (for all: N = 21, Pearson's r > 0.383, p < 0.044) except for the anatomical label (-8,1,47) peak where the relationship failed to reach significance (p = 0.126) (Figure 6.8). For the scatterplots of the correlations of the other 13 peaks, which all show the same pattern (a positive relationship), see Appendix 7C. Ten of these peaks show a positive, significant relationship (for all: N = 21, Pearson's r > 0.452, p < 0.02). The other 3 peaks did not show a significant relationship (for all: N = 21, Pearson's r < 0.312, p > 0.084).



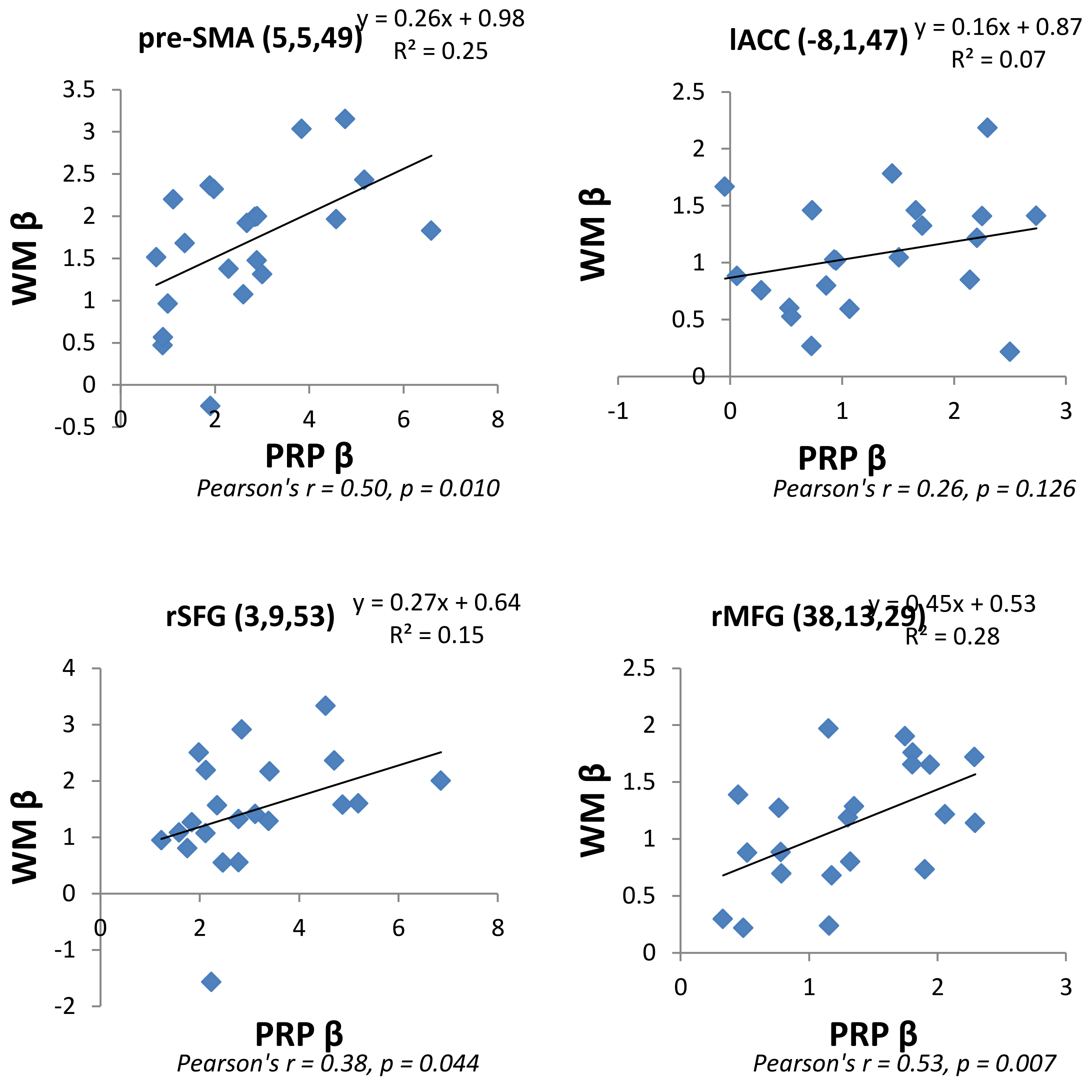


Figure 6.8: Plot for each of the six different peaks showing the correlation between the brain activity in PRP and WM.

Correlation analysis 4. A strong correlation exists between the beta values of the PRP contrast and the WM contrast. If these paradigms share executive functions, also the behavioural performance of both tasks should be positively correlated. If one has good executive functions, they should be good at the PRP task (small DT-costs) and good at the WM task (high memory scores). Because of the nature of the measures, one would expect a negative correlation, but this negative correlation would reflect that performance covaries positively. To test whether the behavioural measures of both task types showed a relationship, Pearson’s correlations were conducted. For the WM task, measures of the recall performance in MST and MDT were used whilst for the PRP dual-task, DT RT2 and error rates in the dual-task were used. Results showed that there was a negative, significant relationship between the recall performance in MST/MDT and the performance in the dual-task (DT RT2/error rates) for three out of the four correlations (for all N = 21, Pearson’s $r > -0.396$, $p < 0.04$). The correlation between MDT recall and both PRP measures was significant as well as the correlation between MST recall and PRP error rates. The correlation between MST recall performance and PRP DT RT2 failed to reach significance (N = 21, Pearson's r = -0.364, p = 0.053) (Table 6.4, Figure 6.9). Summarized results of correlations of the six peaks is given in Table 6.5.

Table 6.4: Results of Pearson's correlations between the behavioural measures of PRP (DT RT2 and DT Error rates) and WM (MST and MDT recall).

Behavioural performance measure	**PRP DT RT2**		**PRP DT Error rates**	
Pearson's correlation statistics	*r*	*p*	*r*	*p*
MST recall performance	-0.364	0.053	-0.499	0.011
MDT recall performance	-0.396	0.038	-0.572	0.004

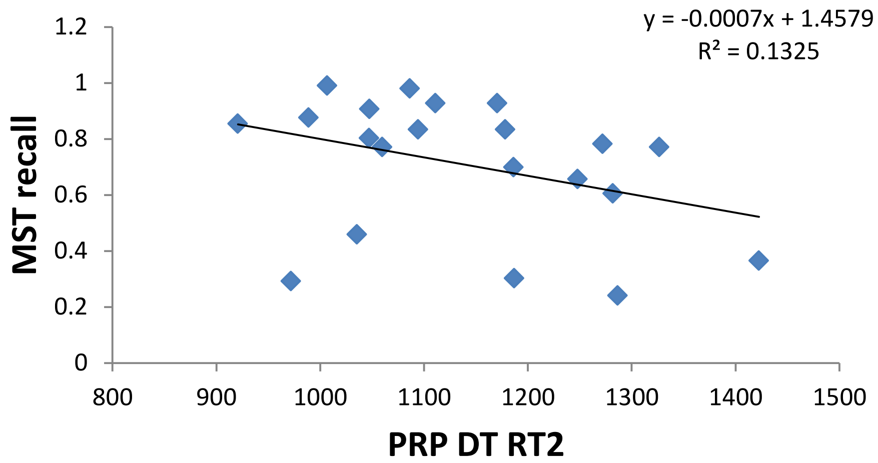


Figure 6.9: Plot showing the correlation between the behavioural performance in PRP (DT RT2) and WM (MST recall).

Table 6.5: Overview of the correlation analyses of the six peaks.

Peak	**Area, Brodmann area**	**PRP β & WM β**		**PRP β & MST Recall**		**WM β & PRP DT RT2**	
(X,Y,Z) coordinate		*r*	*p*	*r*	*p*	*r*	*p*
(48,27,27)	rMFG, BA 46	0.622	< 0.001	-0.262	0.126	0.437	0.024
(-33,5,25)	lIFJ, BA 9	0.405	0.035	-0.636	0.001	0.370	0.050
(5,5,49)	Pre-SMA, BA 6	0.502	0.015	-0.499	0.010	0.228	0.160
(-8,1,47)	lACC, BA 24	0.262	0.126	-0.569	0.004	0.033	0.450
(3,9,53)	rSFG, BA 6	0.383	0.044	-0.374	0.048	0.175	0.224
(38,13,29)	rMFG, BA 9	0.525	0.007	-0.236	0.150	0.401	0.036

6.2.3 Discussion

By combining a PRP dual-task with a complex WM span task, we were able to show that recall performance was lower after performing a dual-task during the retention interval as compared to performing a single task, confirming our earlier behavioural results. Furthermore, participants responded faster in the "processing task only" trials as compared to the "memory + processing task" trials.

The results are in line with the TBRS model which proposes that maintenance as well as processing of information in WM draws on the common limited resource of controlled attention, confirming the results of previous experiments (Chapter 2). A potential reason for responding faster in the "processing only" trials could be that the additional demands in the "memory + processing" trials slowed down the processing task. It could be that participants did trade off some resources from the processing task to support the memory task and hence became a bit slower.

The fMRI results showed DT-specific (contrast DT – AUD – VIS) as well as WM-specific (contrast MST – ST – M) activations which considerably overlapped. In more detail, both areas activated the left IFJ, i.e. the area surrounding the junction of the inferior frontal sulcus (IFS) and the precentral sulcus, the right MFG, the right pre-SMA, the right SFG and the left ACC. With respect to differentiation, the PRP task activated more the inferior middle frontal gyrus (MFG) whilst the WM component activated more the left superior MFG. Beta values of both the PRP and the WM contrast were high indicating that an area which is identified as active in the PRP is also activated in WM and vice versa. Furthermore, several different correlation analyses were performed on the relationship between PRP and WM measures.

PRP and WM indeed seem related to each other by means of common demands on executive functions, since it was possible to predict brain activation in one task with the behavioural performance in the other task. First, there was a significant negative correlation between the PRP beta value and the recall performance in the MST condition indicating that when the brain activity for the PRP dual-task increases, recall performance drops. This also holds vice versa, when the brain activity for the WM task increases, participants become slower in the dual-task. This was confirmed with a significant positive relationship between the WM beta values and the RT2 of the dual-task performance. It has been shown in multitasking and WM research that higher beta values are associated with poorer task performance (Braver et al., 1997; Smith et al., 2001; Szameitat et al., 2016). The typical interpretation is that when participants struggle with the task or when they find the task difficult, they put in more mental effort, which in turn results in higher brain activation in prefrontal areas.

Furthermore, if these paradigms share executive functions, the behavioural performance of both tasks should correlate. If a person is good at WM, they should also be good at PRP. We indeed found such a correlation in the behavioural performance of WM (recall performance in MST and MDT) and the behavioural performance in the PRP task (DT RT2 and DT error rates). Consequently, the beta values of WM (MST – ST – M) and PRP (DT –AUD – VIS) should also correlate with each other, which is indeed what we found. There was a significant, positive correlation between the beta values of the PRP contrast and the beta values of the WM contrast showing that the brain activations have a relationship. Taken together, we have provided evidence that behaviour in one task correlates with beta values in the other task.

A potential criticism of the current study is that part of the analysis is based on visual inspection of overlap in activation of the PRP and the WM contrast. However, the choice of peak coordinates was supported by the calculation of Euclidean distances between potential overlapping peak coordinates and only using one coordinate if the peaks were in proximity of 10 mm or less and localized in the same gross anatomical area.

It might be that although the same gross anatomical areas are activated, the PRP and WM tasks might be subserved by different populations of neurons which are distinct but spatially intermingled in these areas. This might theoretically be resolved by using an fMRI adaptation design, i.e. an event-related design where we could use for instance the following sequence of trials: PRP task, PRP task, PRP task and then WM task. Neurons do adapt to the BOLD signal. The PRP task elicits a certain strong BOLD signal. By repeating the PRP task a few times, we would get the same BOLD signal but reduced in strength/peak (i.e. habitual response). The WM task is presented after a couple of PRP tasks and if then we observe the same lower habituated response, it would indicate that the same neuronal populations are associated with both tasks. However, if the WM shows a higher BOLD response (i.e. no habitual pattern) then this would indicate a different group of neurons eliciting the response.

Also, the PRP task and the WM task are not 100% independent of each other, because they share the single tasks in the two contrasts (DT –AUD – VIS) and (MST – ST – M) where ST is (AUD + VIS)/2. However, it seems unlikely that this can explain the current data because we are interested in the overlap of PRP and WM brain activation to determine whether they share similar executive functions. The single tasks are known to result in much less prefrontal activation than the DT and MST conditions which is, furthermore, differently localised (Szameitat et al., 2002). A similar pattern, i.e. either no prefrontal activity in single tasks or differently located compared to dual-task activation, was found in other research using either the PRP paradigm or other dual-task paradigms (Dux et al., 2006; Herath et al., 2001; Koechlin et al., 1999; Torsten Schubert & Szameitat, 2003).

The fMRI results are in line with the majority of neuroimaging studies presented in Chapter 5 which indicated that WM and PRP paradigms are both associated with frontal regions such as the DLPFC, VLPFC and medial PFC. We found activations in the DLPFC (e.g. right MFG) which is in line with PRP imaging studies who also found MFG and SFG activations for PRP dual-tasks (Stelzel et al., 2006; Szameitat et al., 2006; Szameitat, Schubert, Müller, & von Cramon, 2002). Similarly the IFJ activation we found was also found by others using a PRP paradigm (Schubert & Szameitat, 2003). Activity in the ACC is also in line with previous research (MacDonald et al., 2000; Osaka et al., 2003) and ACC activation can be interpreted as an implementation of control, i.e. monitoring and resolving conflict between tasks. The last region of overlap we found was the SFS which was also found by Szameitat, Schubert, Müller, & von Cramon, (2002) using a PRP paradigm.

To conclude, the behavioural as well as the neuroimaging results support the assumption that PRP dual-tasks demand the executive functions of WM.

Chapter 7 : fMRI study 2

7.1 Experiment 5: fMRI study 2

As described before, WM consists of short-term memory (STM) and executive functions. The first MRI study (Chapter 6) looked at executive functions and in more detail to what extent the executive functions of WM and PRP-dual tasks overlap. Results showed that PRP dual-tasks at least partially demand the executive functions of WM. As a next step, I tried to broaden the scope of the research and looked at the further components of WM beyond executive functions. As indicated, WM does not only consist of executive functions but also of STM. This can be seen as the capacity for the mere holding/maintaining, but not manipulating, a small amount of information in mind. Also, this information needs to stay in an active, readily available state for a short period of time. Both paradigms, PRP as well as WM rely not only on executive functions, but also on STM, in the WM task due to the memory task, and in the PRP task for instance for keeping the S-R mappings available. The next study aimed at disentangling these two components. For this, the next study used a parametric manipulation to investigate the effect of both components of WM, STM and executive functions. Executive functions were manipulated by using two levels, single and dual-tasks in the retention interval similar to the previous studies. STM was manipulated by varying the memory load, i.e. the number of items participants had to keep in an active state for a short period of time in order to recall them later. When the memory load increases, more items need to be kept in storage whilst performing the PRP tasks in the retention interval and hence the demands on maintenance increase. The duration of the retention interval remains the same but participants need to remember more items, whilst focusing on the processing tasks which will increase the demands on controlled attention (which is also needed to perform the processing tasks).

By assessing the independent main effects of task (ST vs DT; reflecting executive functions) and load (low vs high; reflecting STM), the current design allows to test whether there is a distinction between executive functions and load in prefrontal areas, in particular those as observed in the previous study. Furthermore, the TBRS predicts that both, STM and executive functions demand controlled attention, and consequently an interaction between both factors would be predicted. A brain area showing an interaction might be very closely linked to a core component of the controlled attention mechanism.

7.1.1 Method

This experimental design is similar to the first MRI study (experiment 4b), but this time a 2x2 factorial design with both factors having two levels, processing task (single, dual-task) and memory load (3, 6 letters) is used to explore the executive functions in the interaction between processing task and memory load.

7.1.1.1 Participants

Twenty-one (9 female) participants (mean age: 24 years, SD = 5.0, range 19-34 years) took part in the study after having given written informed consent. The study was approved by Brunel University's College of Health and Life Sciences Ethics Committee and participants received £20 for participation. The information leaflet for both MRI and the experiment, consent form for both MRI and the experiment, initial and second screening form for MRI, demographics form, instructions, post-questionnaire and debrief form can be found in Appendix 8.

7.1.1.2 Tasks

The tasks were similar to the previous fMRI experiment (Experiment 4b) described above. The experiment again consisted of a WM span task with preload procedure which consisted of the following phases: cue, memory encoding phase, retention interval processing phase (single or dual-task), recall phase and feedback. This time only trials with a memory component were used and these tasks were performed block-wise. While lying in the fMRI scanner, the participants viewed a projection screen via a mirror. They responded on two separate fMRI-suitable button boxes, each with 5 keys.

Cue. The cue was displayed for 4 seconds and informed the participant about the upcoming trial, for instance "6 letters – Colour Only", or "3 letters Tone -> Colour". Participants had to pay attention to the cue since it would indicate the amount of letters and the type of processing task of the upcoming trial.

Memory Encoding Phase. This component was exactly the same as in Experiment 4b and this time a memory load of 3 and 6 letters were used. Due to these two different memory loads, the overall duration of the memory encoding phase was different for both loads. For a memory load of 3, the memory encoding phase lasted 5650 ms, whilst for a memory load of 6 this was 11050 ms.

Retention Interval Processing Phase. This lasted 24.0 seconds during which the participants performed one of the four processing tasks, i.e. auditory single task, visual single task, dual-task tone -> colour or dual-task colour -> tone. Participants had 2000 ms to respond to the stimuli on each trial. One trial lasted 2400 ms and for the dual-task the SOA was always 0 ms. Again participants got feedback on each trial whether the response was correct, wrong, wrong order (for dual-task) or too slow, which was displayed for 200 ms (instead of 250 ms).

Recall Phase. This component was exactly the same as in Experiment 4b. Again, the duration of this phase was different for both load conditions. The recall phase for memory load 3 lasted for 9 sec. and a memory load of 6 lasted 18 sec. (a row for each recalled letter was presented for 3000 ms).

Feedback. This was similar to Experiment 4b. At the end of each memory trial participants received feedback on their performance in the retention interval. This was displayed for 1600 ms (previously 1700 ms) after which automatically the next trial started.

Processing tasks.

Auditory Single Task, Visual Single Task and Dual-task. These were the same as in Experiment 4b except that the feedback after each trial was shown for 200 ms instead of 250 ms. A retention interval consisted of 10 trials lasting 2400 ms each. In this experiment there was no "No Task" condition.

Procedure. The main experiment was divided into two fMRI runs, containing 19 trials in total (16 memory trials and 3 baselines conditions) and lasting 16 min each. All were randomised, except that each run started and ended with a resting condition which was used as a baseline in which a fixation cross was shown for 24.5 seconds after the cue of 4 seconds. In between the two runs, the anatomical scan was conducted lasting for about 4 min. These trials consisted of 16 different memory trials (8 with memory load six and 8 with memory load three). These 8 trials per memory load were further divided into 4 single task trials (2 auditory and 2 visual) and 4 dual-task trials (2 tone -> colour and 2 colour -> tone). Before performing the experiment in the scanner, participants practiced each of the tasks outside the scanner for approx. 30 min. In total the entire experiment lasted about 1 hour 35 min per participant (40 min MRI scanning, 30 min practice and 15 min paperwork and explanations).

7.2.1.3 MRI Procedure

Two functional runs with 373 volumes each were acquired each lasting for 16 min. All other parameters are as described in fMRI study 1 (see Chapter 6.2.1.3).

7.2.1.4 MRI Data Analysis

MRI data was analysed using SPM 12 (The FIL Methods group, 2017). The same pre-processing steps were used as in experiment 4b consisting of DICOM import, alignment of origin, realignment and unwarp, coregistration estimate, segmentation, normalisation and smoothing. The next steps of the data analysis are the first level (on a subject basis) and second level (all subjects averaged) statistics.

Statistical analysis was based on a voxel-wise least-squares estimation using the general linear model (Friston et al., 1995). Because the current study used a blocked fMRI design, a boxcar function, convolved with a canonical HRF without derivatives, was used to model the BOLD response. For the first level statistics, the encoding, processing and recall phases were all modelled by separate regressors, but for the remaining part of the analyses only the task processing period is of relevance. Nine conditions were used to calculate contrasts of interest (

Table 7.1). MDT is the average of MDTav (first respond to auditory then visual stimulus) and MDTva (first respond to visual then auditory stimulus). A temporal high-pass filter with a cut-off frequency of 1/309 Hz was applied.

Table 7.1: Conditions used in Experiment 5.

3MAUD	Auditory Single Task with Memory Task of load 3
6MAUD	Auditory Single Task with Memory Task of load 6
3MVIS	Visual Single Task with Memory Task of load 3
6MVIS	Visual Single Task with Memory Task of load 6
3MDT	Dual-Task with Memory Task of load 3
6MDT	Dual-Task with Memory Task of load 6

The 2x2 full factorial ANOVA was calculated using the factorial design option in SPM which automatically generates the contrasts necessary to test for the main effects and interaction effect. The design specification proceeds in two stages. Firstly, by creating new factors and specifying the number of levels and name for each of the factors. Two parameters that have to be determined here are the independence and variance. By default, the measurements are assumed to be independent between levels. However, in our design we assume that the measurements are dependent between levels, because we have repeated measures from the same subjects which violates the assumption of sphericity. Also, by default, the measurements in each level are assumed to have unequal variance. However, in our data set we can assume equal variances of the measurements in each level, because the contrasts are all scaled in the same way and it is a repeated measures design from the same subjects. This is in line with the assumption of sphericity. All resulting t-maps were thresholded at $p < 0.05$ (FWE corrected) and if no significant clusters were found, $p < 0.001$ (uncorrected) was considered. Anatomical locations were determined using the Automated Anatomical Labeling toolbox (Tzourio-Mazoyer et al., 2002).

7.1.2 Results

No participants were excluded based on head movement and all participants had behavioural data within 3 standard deviations of the mean, hence there were no outliers.

7.1.2.1 Behavioural results

7.1.2.1.1 Recall performance

To test whether task performance interacts with memory load a 2x2 repeated-measures ANOVA with factors processing task (single, dual-task) and memory load (3, 6 letters) was conducted on the average recall performance. The relative recall was significantly higher in the single task (0.73 ± 0.22) as compared to the dual-task condition (0.62 ± 0.26) (main effect of processing task ($F(1, 20) = 16.93$, $p = 0.001$)). This is in line with our previous studies (experiments 1b, 4a and 4b). Follow-up t-tests showed that ST3 (0.81 ± 0.18) was significantly higher than DT3 (0.65 ± 0.28), $t(20) = 3.38$, $p = 0.003$, but ST6 (0.65 ± 0.27) compared to DT6 (0.59 ± 0.24) was only approaching significance, $t(20) = 1.93$, $p = 0.068$.

Relative recall across task conditions was significantly poorer for memory load 6 (0.62 ± 0.25) compared to memory load 3 (0.73 ± 0.21) (main effect memory load ($F(1, 20) = 33.76$, $p < 0.001$)), which is also in line with previous findings (experiment 1b). When comparing the loads separate for each task, there was a significant difference for the single task between the two loads but not for the dual-task condition. Relative recall in ST3 (0.81 ± 0.18) was significantly higher than relative recall in ST6 (0.65 ± 0.27) ($t(20) = 4.02$, $p = 0.001$), but the difference in relative recall in DT3 (0.65 ± 0.28) was only approaching significance compared to relative recall in DT6 (0.59 ± 0.24) ($t(20) = 1.94$, $p = 0.066$). Processing task and memory load did not interact ($F(1, 20) = 2.74$, $p = 0.11$) (

Table 7.2, Figure 7.1).

Table 7.2: Relative recall performance of Experiment 5 as a function of processing task and memory load.

Variable	Memory Load	
Processing Task	3	6
Single Task	0.81 ± 0.18	0.65 ± 0.27
Dual-Task	0.65 ± 0.28	0.59 ± 0.24

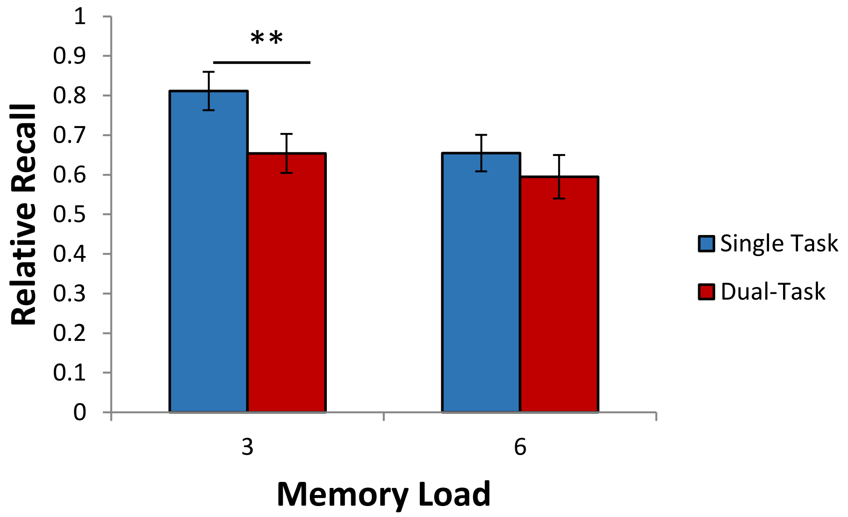


Figure 7.1: Relative recall performance for single task and dual-task conditions of experiment 5 for the two different memory loads. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**. Results of paired t-tests for recall performance differences are shown above each pair of bars of memory load (** p < 0.01).**

7.2.2.1.2 Processing task performance

Response times. To test whether participants responded differently to the different conditions, a 2x2 repeated-measures ANOVA with factors processing task (single, dual-task) and memory load (3, 6 letters) was conducted on the average RT1 (Table 7.3, Figure 7.2). Participants responded faster in the single task condition (510 ± 97 ms) compared to the RT1 of the dual-task condition (797 ± 149 ms) (main effect of processing task $F(1,20) = 120.92$, $p < 0.001$). This effect was present in both memory loads (all $t(20) > 10.31$, $p < 0.001$). As expected the main effect of load was not significant ($F(1, 20) = 1.09$, $p = 0.31$), meaning that RT1s did not differ between memory loads. Processing task and memory did not interact ($F(1,20) = 0.51$, $p = 0.49$).

To see whether the response times of the dual-task differed, a 2x2 repeated-measures ANOVA with factors response time (RT1, RT2) and memory load (3, 6 letters) was conducted (Table 7.3, Figure 7.2). The response times to the first task, RT1, (797 ± 149 ms) were significantly faster than the response times to the second task, RT2, (1096 ± 167 ms) (main effect of response $F(1,20) = 342.59$, $p < 0.001$). This effect was present in both memory loads (both $t(20) > 17.53$, $p < 0.001$). The main effect of load was not significant ($F(1,20) = 0.01$, $p = 0.92$), meaning that response times did not differ between memory loads. Response and memory load did not interact ($F(1,20) = 0.14$, $p = 0.71$).

Table 7.3: Response times in ms and error rates in percentages of the different processing task conditions specified for the different memory loads of experiment 5. Please note that RT2 means and standard deviations for load 3 and load 6 are indeed virtually identical, differing only in decimal places.

Variable	**Memory Load**	
Processing Task	**3**	**6**
DT	RT1: 766 ± 156 ms RT2: 1096 ± 169 ms Error rate: 17.59 ± 12.90 %	RT1: 798 ± 147 ms RT2: 1096 ± 169 ms Error rate: 19.79 ± 13.94 %
ST AUD	RT1: 501 ± 86 ms Error rate: 3.69 ± 4.37 %	RT1: 529 ± 127 ms Error rate: 2.98 ± 3.68 %
ST VIS	RT1: 507 ± 116 ms Error rate: 4.36 ± 8.53 %	RT1: 501 ± 106 ms Error rate: 4.83 ± 9.96 %

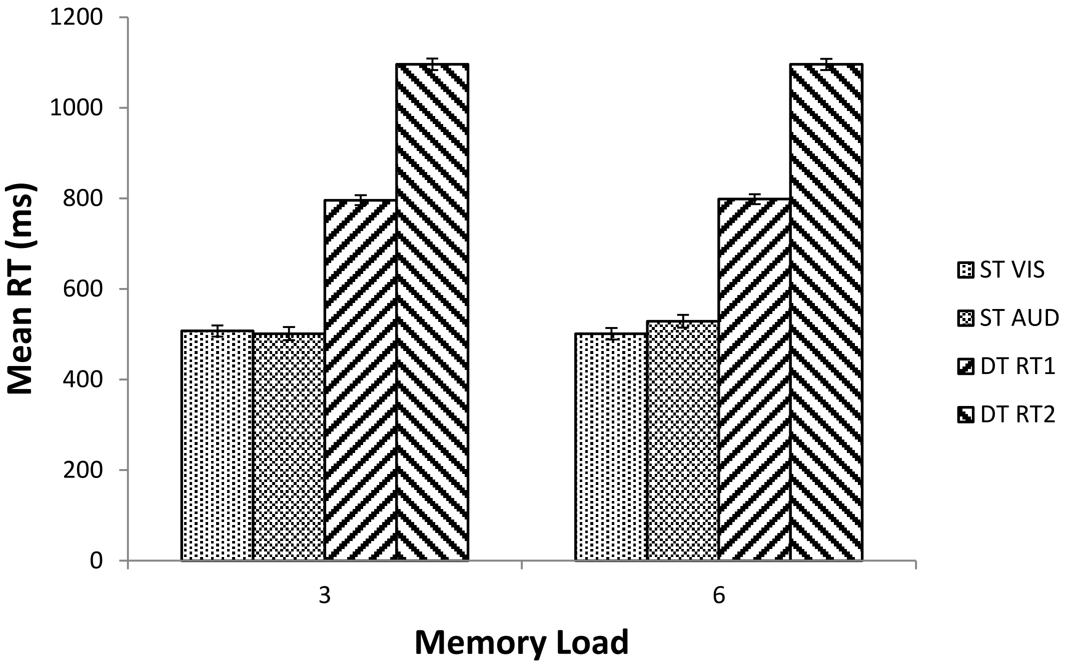


Figure 7.2: Mean response times for the different processing task conditions per memory load of experiment 5. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**.**

Errors. A 2x2 repeated-measures ANOVA with factors processing task (single, dual-task) and memory load (3, 6 letters) was conducted to test whether the error rates of the different tasks and loads were different (Table 7.3, Figure 7.3). Participants made significantly more errors in the dual-task condition (18.69 ± 13.22 %) compared to the single task condition (3.97 ± 5.11 %) (main effect of processing task ($F(1,20) = 51.31$, $p < 0.001$)). This was true for both memory loads (both $t(20) > 6.94$, $p < 0.001$). The main effect of load was not significant ($F(1,20) = 2.62$, $p = 0.12$) indicating that the difference in error rates across loads was not significant. This indicated that the dual-task related RT increases were not due to a speed-accuracy trade-off. Processing task and memory load did interact ($F(1,20) = 4.72$, $p = 0.042$). Participants made significantly more errors in the DT6 condition (19.79 ± 13.94 %) compared to the DT3 condition (17.59 ± 12.90 %) ($t(20) = 2.17$, $p = 0.042$). This was not true for the single task condition across loads. Here, participants made virtually the same amount of errors, i.e. ST6 (3.91 ± 5.69 %) and ST3 (4.04 ± 4.88 %), $t(20) = 0.20$, $p = 0.84$. For both loads the difference in error rates between ST and DT was significant as mentioned above. However, the increase in error rates from ST to DT was more pronounced in load 6 (increase of 15.87 %) compared to load 3 (increase of 13.55 %).

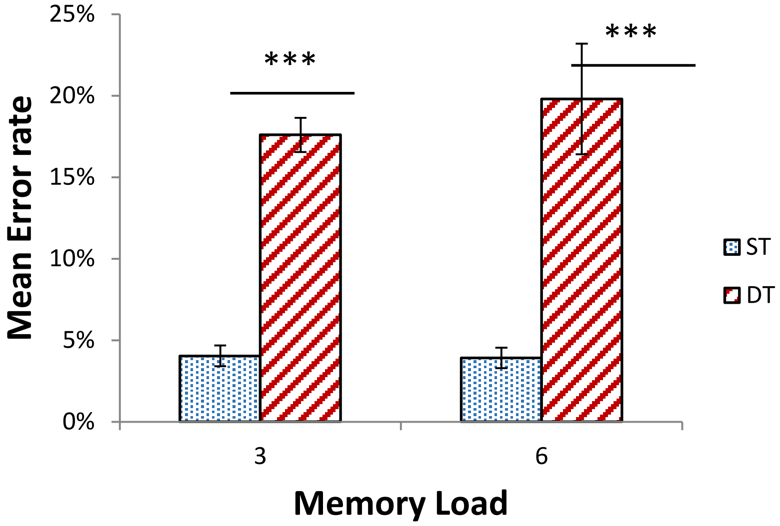


Figure 7.3: Error rates per processing task of experiment 5. Error bars denote 95% confidence intervals (Loftus & Masson, 1994)**. Results of paired samples t-tests for error rate differences are shown above each pair of bars per memory load (*** p < 0.001).**

7.2.2.2 Neuroimaging results

The goal of the present experiment was to disentangle the two components of WM, namely executive functions and STM. Both these components demand controlled attention and therefore there could be an interaction between these components. In the behavioural data, we found some evidence for such an interaction, which was significant in the error rates and approached significance in the response time data.

The fMRI data, as indicated above, was analysed using a 2x2 full factorial ANOVA with factors processing task (single, dual-task) and memory load (3, 6 letters). The main effect of task was inclusively masked with the t-contrast of positive effect of task (uncorrected mask p-value 0.05), which ensured that activations only reflect higher activity in DT as compared to ST (and not also potentially higher activations in ST as compared to DT). The main effect of task showed seven significant activation peaks in the prefrontal cortex (Figure 7.4). While the overall pattern was largely comparable, we observed two additional activation peaks in MRI study 2, namely anterior insula in both hemispheres and lateral-inferior IFG/IFS in the right hemisphere. The MFG (in both hemispheres) was activated much like MRI study 1, but extended more anteriorly (by visual inspection at the chosen thresholds) (Table 7.4).

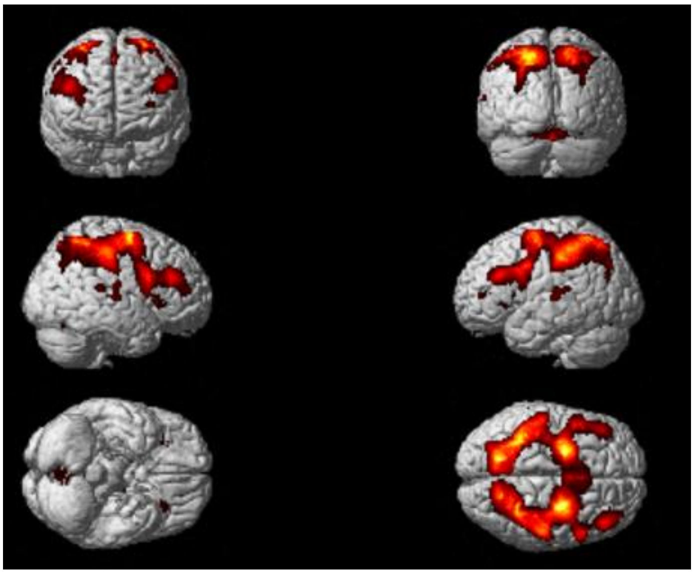


Figure 7.4: Render view showing the results of the main effect of task ($p < 0.05$ FWE) inclusively masked ($p <0.05$, uncorrected) with the t-contrast of positive effect of task.

Table 7.4: Areas showing significant activation for the main effect of task. BA = Brodmann's area, x,y,z MNI coordinates of local peaks. Abbreviation of areas: MFG = middle frontal gyrus, IFG = inferior frontal gyrus, IFS = inferior frontal sulcus.

Cluster	**Area**	**Brodmann area**	**(x,y,z) coordinates**	**F-value**	**z-value**	**p-value peak level (FWE)**
Right hemisphere						
1	rMFG	BA 10	(36,50,12)	31.75	5.02	< 0.001
2	rMFG	BA 46	(42,32,28)	70.33	6.99	< 0.001
3	Anterior insula	-	(30,26,4)	65.83	6.81	< 0.001
4	rIFG, rIFS	BA 9	(40,14,24)	72.23	7.06	< 0.001
Left hemisphere						
5	lMFG	BA 46/10	(-32,42,8)	34.11	5.19	< 0.001
6	Anterior insula	-	(-30,20,6)	61.64	6.64	< 0.001
7	lMFG	BA 9	(-46,4,34)	107.91	Inf	< 0.001

These activations are shown in more detail in Figure 7.5 for the two peaks with the highest F-values.

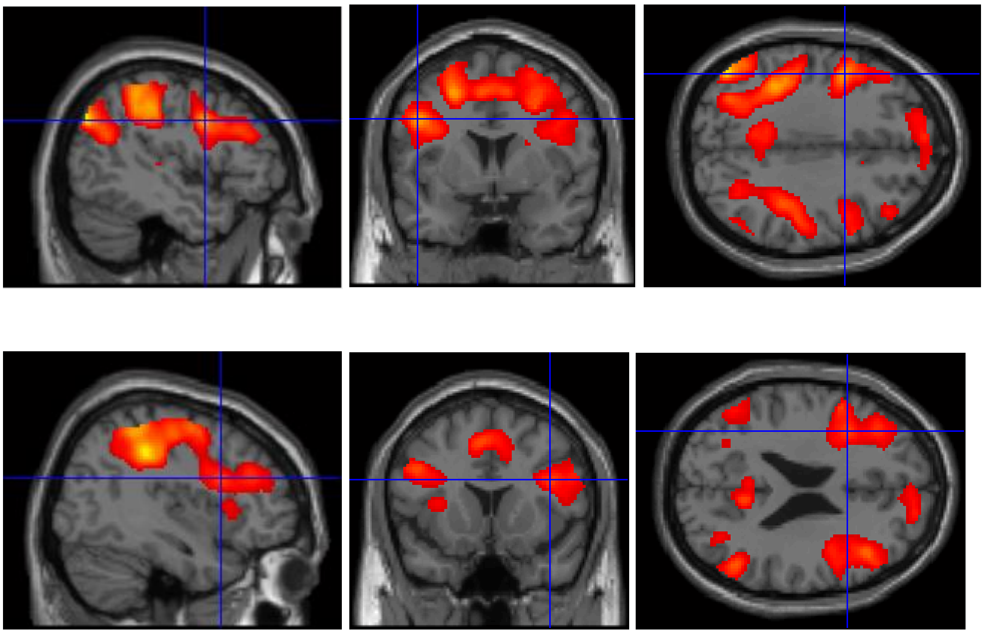


Figure 7.5: Main effect of task (p < 0.05 FWE) shown for peak (-46,4,34), top panel and for peak (40,14,24), bottom panel.

For the main effect of load, it was expected that load of 6 letters would impose increased demands on STM compared to load of 3 letters. For the main effect of load, also inclusive masking ($p < 0.05$ uncorrected) was used to ensure that only areas showing higher activation in load 6 as compared to load 3 were shown. However, the main effect of load did not show any significant activation when a threshold of $p < 0.05$ (FWE) was used. Even when a more liberal threshold of $p < 0.001$ (uncorrected) was used, there were no activations.

If processing task and memory load demand the same processes, e.g. attention according to the TBRS model, they would demand similar brain areas. In other words, rehearsal of the letters and performing the PRP dual-task would require the same processes and an interaction effect is predicted. However, there were no significant prefrontal activations (at $p < 0.05$ (FWE)) for the interaction between processing task and memory load when the interaction term was inclusively masked with the positive effect of processing task x memory load to ensure that only over-additive activations are shown. When the threshold was reduced to $p < 0.001$ uncorrected, again no significant prefrontal activations were found. There were also no significant prefrontal activations at $p < 0.05$ FWE or at $p < 0.001$ uncorrected for the interaction between processing task and memory load when no masking was used. Also the reversed masking was used to test for the opposite effects, i.e. an under-additive interaction, or areas which are more strongly activated in load 3 and ST as compared to load 6 and DT, respectively. However, this reversed masking did not reveal any activations, even at a liberal threshold of $p < 0.001$, uncorrected).

7.1.3 Discussion

This experiment used a 2x2 design with factors processing task (ST and DT) and memory load (3 and 6) to investigate the separate effects of executive function and STM demands and their neuroanatomical correlates. Behaviourally, results showed that the main effect of task was significant, i.e. participants recalled more letters in the single task as compared to the dual-task condition. Furthermore, the main effect of load was significant, i.e. participants remembered more letters in memory load 3 compared to memory load 6. These two effects are in line with previous studies (Chapter 2). In the current study processing task and memory load did not interact on recall ($F(1, 20) = 2.74$, $p = 0.11$). This idea of no interaction is supported by previous behavioural experiments (Chapter 2) which did not find an interaction effect between processing task and memory load on recall ($p > 0.51$). However, this experiment did find an interaction between processing task and memory load in the error rates. The increase in error rates from single task to dual-task was more pronounced in memory load 6 compared to load 3 and participants made significantly more errors in DT6 compared to DT3 whilst this was not the case for the single task conditions across loads.

The neuroimaging results showed a main effect of task with significant activations in the prefrontal cortex (mainly in the MFG and anterior insula in both hemispheres), which confirms and replicates the findings of experiment 4b, i.e. fMRI study 1 (Chapter 6) and is in line with previous PRP dual-task studies (Schubert & Szameitat, 2003; Stelzel et al., 2006; Szameitat, Schubert, Müller, & von Cramon, 2002). When memory load increases, demands on maintenance increase (increased demands on STM) and it was predicted that there were differences in brain activation between the two memory loads. However, the main effect of memory load was absent in the fMRI results even when a liberal threshold of $p < 0.001$ uncorrected was used. This might mean that controlled attention is demanded in the same way for memory load 3 and 6. In other words, STM/maintenance demands controlled attention but the parametric manipulation on the demands failed since the load manipulation did not increase the attentional demands associated with memory load.

An interaction effect was predicted between the independent manipulations of executive functions and STM demands leading to the demands on similar brain areas. However, there were no significant prefrontal activations for the interaction effect. Potentially, the logic behind the experiment has to be addressed. Absence of a load effect (due to a sub-optimal experimental design) means that we potentially only investigated only one factor, i.e. processing task (executive function demands). The other factor (memory load) was not well manipulated, i.e. it was constant across the levels of the task factor, which is equivalent to not including it in the design in the first place. If only one factor is investigated, there can be no interaction.

The absence of a main of effect of load might be explained by scrutinizing potential rehearsal strategies. Suppose participants would be overtly rehearsing during the retention interval, then the demands on a rehearsal processes such as the phonological loop are not necessarily higher for higher memory loads. This is because one just constantly repeats letters, in one case six and the other three which does not require more demands. However, one may have predicted that the demands changed if for instance the speed of rehearsal would have changed, i.e. participants would have tried to say the letters quicker in load 6 than in load 3. This is explained by the word-length effect of Baddeley (1986, 1997) which states that the phonological loop is limited to storing verbal information which can be said in 2 seconds. Therefore, participants might try to speak more quickly for load 6 to squeeze more into the 2 seconds before decay occurs. If that would be indeed the case, then this should result in higher demands on the phonological loop/maintenance-related controlled attention. However, our data suggest that participants rehearsed at a rather similar pace, irrespective of load, no matter how many letters there were and probably just rehearsed ("ran through") the sequence of three letters more often during the retention interval compared to six letters. A reason for this might be that already at load 3 they are rehearsing at a rather high speed (ceiling effect). Alternatively, it might be that participants actually do not rehearse overtly or covertly, but that instead rehearsal is done by some automatic process. However, no matter what the rehearsal process is, it seems to operate always at the same speed, i.e. it occupies the same amount of controlled attention and, as a consequence, memory recall decreases at higher loads.

Furthermore, participants could use different strategies to perform well in the tasks. This could be addressed in future studies by for instance manipulating the type and speed of rehearsal. Participants could be instructed to rehearse either overtly or covertly with similar pace by using a cue (e.g. a beep) indicating when a new type of rehearsal is allowed. Results would indicate whether the type of rehearsal has an effect on memory performance. Also, the speed of rehearsal could be manipulated. This could be done for instance by training participants to engage in different rehearsal speeds, and then instructing them which speed to use during the main experiment. Results would indicate what effect rehearsal speed has on the STM demands.

Other research has found an effect of WM load (and not STM demands) on prefrontal cortex activations. For instance, Manoach et al. (1997) found that when a high WM load choice reaction time task was compared to a low WM load condition significant activations were found in the DLPFC, SMA and intraparietal sulcus (IPS). Another study by Rypma & D'Esposito (1999) used a WM task and found that the effects of increased memory load were observed only in right dorsal PFC in the encoding period. Participants showed a greater activation in right dorsal PFC for the high memory load (6 letters) compared to the low memory load (2 letters).

In this thesis, the focus is on verbal WM and not spatial, since it is known that they are subserved by different rehearsal mechanisms (both cognitive and underlying neuroanatomical correlates). However, to the best of my knowledge I did not find studies that reported different brain activations due to an increase in memory load in a verbal STM task. This might be due to potential publication bias, since null findings are hardly reported. The current study also reported a null finding i.e. an absence of the main effect of memory load in brain activation. This means that a mere increase in memory load for verbal material (e.g. letters in the current study) does not necessarily always implies an increase in the demands on controlled attention. This should be reflected in models of controlled attention like the TBRS model and may inform future studies. This might only hold true for verbal material and that for spatial/visual material the effects might be different, which is not incongruent, because the rehearsal mechanism is potentially very different for verbal and spatial stimuli (see (Linden et al., 2003)).

Chapter 8 : Discussion and Conclusion

The aim of this thesis was to explore the relationship between WM and multitasking. In more detail, the aim was to investigate to what extent PRP and WM share executive functions. For this purpose, a complex WM span task was created that combined a simple span task (memory) with a PRP dual-task. The behavioural experiments were founded on the assumption that if the additional dual-task processes are related to the controlled attention of WM, then the performance of a PRP dual-task should interact with a complex WM span task, e.g. by affecting memory maintenance performance as indicated by the TBRS model of WM (Barrouillet & Camos, 2007). Several different behavioural experiments were conducted using different variations of the PRP dual-task and its individual single tasks as processing tasks during the retention interval to measure the effect on the recall performance. In each experiment, participants were presented with a PRP paradigm in which they had to perform either a single task (auditory or visual) or a dual-task (fixed or random order) while remembering letters that were presented during the memory encoding phase. After the retention interval, the letters had to be recalled in the same order as they were presented. The first experiments focused on the effect on recall performance by performing either a single or a dual-task in the retention interval. In all memory load conditions, recall performance was significantly lower after performing a dual-task during the retention interval as compared to performing a single task. The PRP dual-task demands more controlled attention than the single task and hence more strongly interferes with memory recall. Therefore, maintenance as well as performing a PRP task draws on the common limited resource of controlled attention which is in line with the TBRS model (Barrouillet & Camos, 2007, 2010). Higher demands on controlled attention by the processing task mean that controlled attention is demanded for a longer period of time, so that there is less time available to refresh the memory traces for maintenance of information (Barrouillet & Camos, 2007). This provides first evidence that the PRP dual-task demands attentional control (executive functions) and that these control processes are related to the controlled attention component of WM.

The next set of experiments used a parametric manipulation namely the effect of task order on recall performance. The same paradigm was used, but now participants had to either perform a difficult dual-task condition (random order) or an easier dual-task condition (fixed order) during the retention interval whilst memorizing the letters for recall. The difficulty between the two dual-tasks lies in the demands on task-order coordination (Schubert, 2008; Szameitat et al., 2006). Previous research has shown that if people have to respond in a certain order they automatically prepare to respond to the next trial in the same order as the previous trial (De Jong, 1995). Results showed that recall performance was lower after the random order dual-task as compared to the fixed order dual-task. This shows that the demands on executive functions are increased due to the additional demands the random order dual-task places on the attentional control system. Inhibition and switching of the response order takes place to make sure the responses are given in the correct order (De Jong, 1995; Luria & Meiran, 2003). This is again in line with the TBRS model since the random order dual-task requires more controlled attention meaning there is less time available for memory rehearsal in this condition (Barrouillet & Camos, 2007). A follow-up experiment used two different random order dual-task conditions, one with two switches between the two response orders and one with nine switches. Results showed that the recall performance was significantly higher after the low switches as compared to the high switches, again in line with the TBRS model (Barrouillet & Camos, 2007). The more difficult dual-task (more switches) puts higher demands on controlled attention and this leads to lesser time available for memory rehearsal. Again this supports the idea that PRP dual-tasks demand the executive functions of WM. However, a replication experiment did unfortunately not show the same results. Although the relative recall was, as expected, numerically lower in the high switch condition compared to the low switch condition, this difference did not reach significance. Future research is needed to study other potential effects that could be interfering like task difficulty, processing of stimuli, optimal trial duration.

The last behavioural experiment manipulated the SOA (short vs long) in the dual-task to study the effect on recall performance. Results showed that time on task, i.e. time spent on the task which is according to TBRS the predictor of how much controlled attention is needed by the task, was significantly shorter for the short SOA compared to the long SOA. According to the time on task theory, this suggests that the long SOA occupies attention actually for a longer time compared to the short SOA and hence it predicts that recall performance is poorer in the long SOA. Theory-based proposed demands on executive functions predict the opposite: short SOAs demand more executive functions due to the higher temporal overlap, i.e. more interference between the tasks and hence predict that recall performance is poorer in the short SOA. Results did not support these predictions which means that it is not only time on task that plays a role but that executive functions play a role too, namely that the nature of the processes demanded during the time on task is important. The TBRS model refers to the demands and attention needed to perform the task, but this research has added that it is also about the nature of the demands, and not only the demands per se. This may indicate that the TBRS model uses time on task as the time spend on central processing stages, but not peripheral (but see Liefooghe et al., 2008 who showed that also time spent in peripheral stages can affect WM recall).

In sum, these behavioural experiments support the assumption that PRP dual-tasks demand the executive functions of WM. It indicates that dual-task performance relies at least partially on the same cognitive processes as WM. Next, a literature review on the neuroimaging literature on both multitasking and WM was conducted to understand the brain mechanisms of executive functions in more detail. This was followed by two fMRI studies in order to answer the research question whether the executive functions of PRP and WM are subserved by similar brain areas.

Neuroimaging studies on multitasking have shown that mainly a fronto-parietal network is involved in the processing of two tasks at the same time (Miller, 2000; Stelzel et al., 2006; Szameitat, Schubert, Müller, & Von Cramon, 2002). When using the PRP paradigm, one can ensure interference on a response level and in these studies dual-task specific activation is shown (Schubert & Szameitat, 2003; Stelzel et al., 2008; Szameitat, Schubert, Müller, & Von Cramon, 2002). In more detail, dual-task specific activation is often found in regions like MFG, SFG, IFJ and IFS (Schubert & Szameitat, 2003; Stelzel et al., 2006; Szameitat, Schubert, Müller, & Von Cramon, 2002).

To study WM, often complex WM span tasks are used which use inhibition, shifting and updating, such as the listening, reading and operation span task (Chein et al., 2011; Kondo et al., 2004; Osaka et al., 2003; Smith et al., 2001). Research on the neuroanatomical correlates of WM (executive functions and storage) has shown that WM processing is associated with activations in prefrontal areas like DLPFC, ACC, MFG, and IFG (Carter et al., 1998; D'Esposito et al., 1995; Linden, 2007; MacDonald et al., 2000; Mansouri et al., 2009; Rushworth et al., 2004; Salmon et al., 1996; Smith & Jonides, 1999).

Taken together, previous imaging studies have indicated that WM and PRP tasks are both associated with frontal regions such as MFG, IFG and ACC. However, differences in the exact activation patterns are observed across studies when looking in more detail. Therefore, in this thesis two fMRI studies were presented to investigate whether the same brain areas in the prefrontal cortex are activated when participants perform a complex span task involving a WM and a dual-task component. Participants performed again the complex WM span task, i.e. remembering letters whilst performing either a single or a dual-task in the retention interval, whilst lying in the scanner.

Results showed considerable overlap in mainly prefrontal areas such as DLPFC, VLPFC and medial PFC for WM and dual-task performance. Both tasks showed increased activation in the left IFJ, right MFG, left SFS, which is in line with previous research who also found those areas in PRP paradigms (Schubert & Szameitat, 2003; Stelzel et al., 2006; Szameitat, Schubert, Müller, & Von Cramon, 2002). This overlapping brain activation indicates that PRP and WM rely on similar processes and mechanisms in the brain.

PRP and WM indeed seem related to each other by means of common demands on executive functions, since it was possible to predict brain activation in one task with the behavioural performance in the other task. This was shown by negative, significant correlations between PRP beta and WM behavioural performance and vice versa, i.e. negative, significant correlations between WM beta and PRP behavioural performance. Also, if a person is good at WM, they should also be good at PRP which was shown in significant correlations between the behavioural performance in WM and the behavioural performance of PRP and consequently also in the correlation between the beta values of both WM and PRP. This indicates that dual-task performance and WM both rely at least partially on the same functional neuroanatomical correlates. My interpretation is that this anatomical overlap is caused by the fact that both demand the same executive functions.

WM does not only consist of executive functions, but also of STM. Both paradigms, PRP as well as WM rely besides executive functions, also on STM. The second MRI study aimed at disentangling these two components.

Results however, only showed a main effect of task with significant activations in the PFC (mainly in MFG and anterior insula in both hemispheres) which confirms the findings of the first MRI study and previous research on PRP dual-task (Schubert & Szameitat, 2003; Stelzel et al., 2006; Szameitat, Schubert, Müller, & Von Cramon, 2002). The main effect of load as well as the interaction between processing task and load did not show any significant brain activations. The absence of a main effect of load might mean that the two memory loads demand controlled attention in the same way. This suggests that increasing memory load by a number of letter does not necessarily increase demands on controlled attention.

To conclude, the behavioural as well as the neuroimaging results showed that PRP dual-tasks demand executive functions and that these are the executive functions of WM. Both paradigms activated similar regions and showed a strong overlap which suggests that both paradigms rely on the same cognitive processes, i.e. they rely on the same executive system.

Thus, the results presented here established important groundwork on the concept of executive functions in the PRP paradigm. The literature on PRP and on WM is traditionally rather separate, as both paradigms are founded in different research communities. Both communities come from very different backgrounds; WM form memory and PRP research from action. Nevertheless, both have used the term executive functions in similar ways. Executive functions are discussed in two separate streams of literature and this research has bridged two pretty independent research communities, both using similar terminology (executive functions, inhibition, monitoring etc.). In this thesis I was able to show that they are actually referring to the same mental processes. The results presented in this thesis allow us to inform theoretical models of cognition and to get a better understanding of human cognition. Future studies can build on this in order to create a more consolidated conceptualisation of the relationship between WM and multitasking. In more detail, the results of the study give more insight into executive functions. According to the TBRS model, it is all about the time on task which is a predictor how much controlled attention, e.g. executive functions, is needed by the task. Results indicated that this time on task more specifically may be the time spent on central processing stages and not peripheral ones, which is how time on task is described by others, e.g.Lewandowsky & Oberauer, 2015). Furthermore, time on task is a too unspecific measure, because it assesses a lot more than just the central processing times, especially in a complex working memory task where there is also the refreshing stage. All available time not used by the processing task (dual-task) is used for refreshing the items in working memory. However, I would argue that this refreshing mechanism (no matter what strategy the participant uses) also demands controlled attention which is again the central bottleneck. This means that time on task might not be an optimal indicator to measure how much time is spent on controlled attention, it merely indicates the time spent on the processing task. It is not clear how the TBRS model measures the refreshing mechanism. Further research could explore this area.

The results suggest that the concept of executive functions according to the TBRS model and the concept of executive functions according to human action performance research are actually linked. This leads to potential additions to existing models such as Baddeley and Hitch (1974) which described executive functions as the central executive system receiving input from the phonological loop and the visuo-spatial sketchpad. The results described in this thesis indicate that this central executive system is linked to the executive functions of working memory (TBRS model). This might have an effect for the role of the episodic buffer, which according to Baddeley holds and integrates information from the two slave systems but also from long-term memory (Baddeley, Allen & Hitch, 2011). There might be a closer link between the episodic buffer and the central executive system who probably work very closely to give the desired output. Another model that has been used is the supervisory attentional system (SAS) by Norman and Shallice (Norman & Shallice, 1980). Here, the SAS is involved in the higher level control of action and is the executive component of task coordination. Current results might indicate that the role of the SAS is even broader when it is linked to the executive functions of working memory. Finally, current results imply for Engle's model of working memory that controlled attention is perhaps not only important for higher-order functioning but also task-processes (Engle, Kane, & Tuholski , 1999).

The research findings are in line with the active scheduling account of how tasks are processed in the presence of a bottleneck. Furthermore, this active scheduling account predicts that the central attentional bottleneck in the PRP paradigm demands executive control. Results showed that this is indeed the case; dual-task processing demands executive functions of WM beyond the single task as shown by reduced recall performance in the dual-task condition. This is due to the executive functions related to active scheduling in the dual-task occupying controlled attention for a longer time than in the single task, which leaves less time and attention for rehearsal of the memory items. Additional processes such as inhibition, switching, and monitoring are involved in coordinating task processing at the bottleneck, which are related to the executive functions of WM. Also additional activation in brain areas mostly in the lateral prefrontal cortices is found relating to these scheduling demands. These results are all in contrast with the passive queuing account, where tasks are processed on a first-come, first-served basis and does not predict increased cognitive demands relating to task performance.

So far, working memory dual-tasks, like complex working memory span tasks have been treated rather separately from PRP dual-tasks. This current data suggests that there is no need for that. The PRP paradigm can be used to investigate working memory which opens up a completely new perspective on studying working memory. This also works the other way around, complex working memory span tasks can be used to provide a different perspective on multitasking research.

The current results can have implications for real life scenarios. For instance, when a PRP situation occurs (e.g. while driving a car), this does not only result in a deferment of a response or processing of the second stimulus, but also the occupation of central resources which are then not available to other processes. These other processes might be important, e.g. dealing with some critical traffic situation for which a decision needs to be made rather quickly. Along the same lines, the current findings can also affect the design of human-machine interfaces and human-computer interfaces.

8.1 Limitations

The experiments described in this thesis have several limitations. First, for all experiments, the participants were students and hence they are not a randomly chosen sample from the general population. Also, memory can be measured in different ways and in these experiments, serial recall was measured, i.e. recalling the letters in the same sequence as presented. In the literature it is most common to measure serial recall when talking about executive functions. Serial recall is more demanding due to the constraint of remembering the items in the same sequence and hence requiring more executive functions (updating and monitoring) than for instance free recall where participants just need to remember the items (and not in a particular order). However, free recall could also be used to determine memory performance and this could lead to different results. Actually, an undergraduate dissertation student did an experiment on this and used the same paradigm as in experiment 1b but measured free recall instead of serial recall. Results showed that in general memory performance is higher for free recall compared with serial recall. However, also for free recall, the memory performance in single tasks was significantly higher than recall in dual-tasks. This indicates that even in the free recall condition, executive functions are needed for the processing of the tasks.

Another limitation is in fMRI study 2 in which participants may have used an unpredicted strategy and hence could explain why we did not find an effect of memory load or an interaction between processing task and memory load. In general, strategy could influence the results. It is not entirely clear what strategy participants used to perform the PRP task and at the same time rehearse the items in memory for later recall. We did ask in the post-questionnaire how they rehearsed the letters, and we found that participants either rehearsed them letter by letter (by repeating the letters in their head) or by making words/sequences out of the letters in order to remember them. However, some participants used a mix of these two potential strategies.

In general, there were quite some difficulties in making the experiment work. Especially in Chapter 3, a few pilot studies were needed to fine-tune the parameters and confirm the hypothesis. Potentially, some of the effects depended on rather small details in the experimental design, which, however, is not uncommon in cognitive psychology. The study in Chapter 3 was about how two very similar dual-task conditions (random-high vs random-low) interact with a concurrent short-term memory task. This is a very fine-grained manipulation, which is expected to affect another process, i.e. STM, which seems to be effective only in case of a fine-tuned paradigm. However, we do need more replication studies.

8.2 Future research

A deeper understanding of the concepts of WM and multitasking allows for a better understanding of human cognition. Furthermore, it can also give insight into strategies that are used to deal with the demands of multitasking situations effectively. As mentioned it would be interesting to explore the strategies participants used to perform the tasks well, both the PRP paradigm and the memory component.

Also, further research can explore the relationship between WM capacity and multitasking. Again, here one can think of different strategies that are potentially used by individuals with high working memory capacity versus low working memory capacity (high versus low span). This is related to an interesting aspect which is individual differences and how these could potentially be used as predictors of performance. Finally, on a more practical note, research on multitasking and memory could improve high demand work environments where workers must simultaneously monitor multiple systems that are independent of another and make quick decisions based on the results. This involves a lot of the aspects of executive functions, namely monitoring, updating, switching, coordinating and planning.

The present results could have clinical implications, e.g. for patients with clinical symptoms such as dementia which affect the PFC, or patients with PFC lesions. It could have implications for diagnosis, rehabilitation and occupational therapy. It would be interesting to transfer the experiments as described in this thesis to patients. Further research needs to be done to determine the extent and practicalities of these implications.

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Appendix 1: Documents experiment 1a, 1b

This appendix outlines the different documents used for the experiments. Every experiment has an ethics confirmation letter (Appendix 1A), an information sheet (Appendix 1B), a consent form (Appendix 1C), a demographics form (Appendix 1D), an instruction paper (Appendix 1E), a post-questionnaire (Appendix 1F), a debrief form (Appendix 1G) and receipts (Appendix 1H). Appendix 1 gives these forms for experiments 1.

For experiment 1b, the same forms (information sheet (Appendix 1B), consent form (Appendix 1C), demographics form (Appendix 1D), debrief form (Appendix 1G) and receipt (Appendix 1H) as experiment 1 were used except the instructions sheet was changed, Appendix 1I. Also questions 10 till 13 were added to the post-questionnaire as can be seen in Appendix 1J. The following appendices outline the forms that deviate from these forms per experiment.

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Appendix 1A: Ethics approval for experiments 1a and 1b

School of Social Sciences Ethics Checklist

ETHICAL MATTERS MUST BE CONSIDERED BEFORE ANY RESEARCH TAKES PLACE
FAILURE TO FOLLOW THE CORRECT ETHICAL PROCEDURESOR CONDUCTING RESEARCH WITHOUT ETHICAL APPROVAL WHERE IT IS REQUIRED MAY LEAD TO DISCIPLINARY ACTION

Guidance

This Ethics Checklist has been designed to help determine the level of risk or harm to participants' welfare entailed in a proposed study. It also contains a sample consent form and information leaflet checklist that you can use/adapt as appropriate.

NB: If your research requires NHS ethics approval, you should not complete this form. Please provide the School with a copy of your letter of NHS approval once you receive this.

Who Completes the Checklist?

The Principal Investigator (PI) is the main researcher and can be a student. The PI (or where the PI is a student, the supervisor) is responsible for exercising appropriate professional judgement in this review.

Underpinning Codes of Ethics

Before completing this checklist, you must refer to the University Code of Research Ethics as well as the relevant code of ethics for your discipline. These are listed in the Useful Links section at the end of this guidance. It is your responsibility to follow these Codes of Research Ethics in the conduct of your study. This includes providing appropriate documentation and ensuring confidentiality in the storage and use of data (see section 3.3.2 of the University Code of Research Ethics).

The Checklist

This Checklist is in two parts:
Part 1: This must be completed by all students and staff undertaking research. This section aims to that there are no ethical or risk assessment issues related to your research.
Part 2: This is for all Principal Investigators who identify that there are ethical and/or risk assessment issues in their proposed research.

YOU MUST HAVE YOUR APPLICATION, CONSENT FORM AND INFORMATION SHEET APPROVED BY YOUR DEPARTMENTAL ETHICS COORDINATOR (OR IF APPROPRIATE, UNIVERSITY ETHICS COMMITTEE) BEFORE YOU START YOUR RESEARCH AND APPROACH POTENTIAL PARTICIPANTS.

What do I have to do if I need to complete the University Research Ethics Committee Application Form?

You will need to complete and submit this via BBL. In most cases, the School will be able to review and approve the ethics form. If the research needs University level approval, your form will be submitted to the University Research Ethics Committee by the Research Office.

Risk Assessment

All Principal Investigators (and their supervisor where relevant)are required to consider matters of risk an conduct a risk assessment as part of the University's Health and Safety Policy. If issues of risk are identified, a risk assessment is required and must be attached to this form. For further information about Risk Assessments and guidance on how to undertake one, see the document 'RISK ASSESSMENT – FAQs' which can be found in the School of Social Sciences Ethics Organization, under my Organizations in BBL.

Disclosure and Barring Service (formerly Criminal Record Bureau) Checks

If your research involves vulnerable persons, you are required to follow University guidelines for Disclosure and Barring Service (DBS) checks. If you need a DBS check please contact the DBS Administrator in Admissions who will send you the information you need to make a DBS application.

How to submit Checklist and appendices on Blackboard Learn

Stage 1: Log into BBL

Stage 2: Click on the School of Social Sciences Research Ethics Organisation, under the My Organisations list on the right hand side

Stage 3: Download the Ethics Checklist from the folder on the homepage titled 'Research Ethics Application Form'.

Stage 3: Click on your appropriate department folder

Stage 4: Click on the Ethics Checklist Submission Assignment Tool

Stage 5: Upload your Ethics Checklist and appendices e.g. consent form, information leaflet, using the Browse My Computer link, and ensure you have uploaded the correct documents

Stage 6: Once you have confirmed they are the correct documents, click submit

Stage 7: You will receive an email receipt of your submission to your Brunel email account

Stage 8: Click on the My Grades link in the School of Social Sciences Research Ethics Organisation to find the outcome and feedback once it has been reviewed by your Departmental Ethics Coordinator.

Further information about how to submit is available in the School of Social Sciences Ethics Organisation, under My Organisations, in BBL.

What happens after I have received ethical approval?

Once you have received ethical approval, you can start your research.

Students are required to retain a copy of the approved Checklist, consent form and information leaflet and submit these with their research report/dissertation/thesis.

All undergraduate and postgraduate work submitted/conducted without ethical approval may be subject to academic penalties and disciplinary action.

If your research is delayed and will extend beyond the dates stated on your form, please contact your Departmental Ethics Coordinator to seek approval for an extension.

Useful Links and Resources

University Research Code of Ethics LINK
UREC website --- LINK
Code of Ethics – Anthropology LINK
Code of Ethics – Economics and Finance (Use University Research Code of Ethics)
Code of Ethics – Politics and History (Use University Research Code of Ethics)
Code of Human Research Ethics – Psychology PDF
Code of Ethics – Sociology and Communications --- LINK

Risk Assessment – FAQs – School of Social Sciences Ethics Organisation, under my Organisations in BBL.

Contacts

Anthropology Ethics Coordinator:	Dr Isak Niehaus
Economics and Finance Ethics Coordinator:	Professor Frank Skinner
Politics and History Ethics Coordinator:	Dr John MacMillan
Psychology Ethics Coordinator:	Dr Achim Schutzwohl/ Dr Bridget Dibb
Sociology and Communications Ethics Coordinator:	Dr Simon Weaver

Research Ethics Administrator:	Ms Amreen Malik

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SSS Research Ethics Review Checklist – Part 1

Section I: Project details

1. Project title: The role of executive functions in working memory and dual---tasking	
2. Proposed start date: 23/02/2015	3. Proposed end date: 30/06/2015

Section II: Applicant details

4. Name of researcher (applicant)	Pauldy Otermans
5. Student Number	1429594
6. Status	PGR Student
7. Department	Psychology
8. Brunel e---mail address	Pauldy.otermans@brunel.ac.uk
9. Telephone number	07518225153

Section III: For students only

10. Module name and number:	Psychology PhD
11. Supervisor's name:	Andre Szameitat
12. Brunel supervisor's e---mail address:	Andre.szameitat@brunel.ac.uk

	Yes	No
13. Does this research involve human participants?	◉	○
14. Does this research raise any ethical or risk concerns as set out in the University Code of Research Ethics or relevant disciplinary code?	○	◉
15. Risk Assessment – are there any elements of risk related to the proposed research? (See Risk Assessment – FAQs)	○	◉

If you have answered **Yes** to any of questions 13---15, you must **complete Part 2** of this form.

Students: If you have answered No, please email this document to your supervisor who will confirm that the research does not involve ethical issues. Once electronically signed by your supervisor, please submit Part 1 of this form via BBL within 1 week. Please keep a copy for yourself and bind it into your dissertation/thesis as an appendix.

Staff: If you have answered No, please sign below and submit your form via BBL. Please keep a copy for yourself.

If your research methodology changes significantly, you must submit a new form.

For Supervisor's/Staff e--- signature

I confirm that there are no ethical or risk issues relating to this research and the applicant can proceed with the proposed research.
e---signature/ Date:

SSS Research Ethics Review Checklist – Part 2

Section IV: Description of project

Please provide a short description of your project:

The aim of this study is to understand the role of executive functions in multitasking. One of the key theoretical concepts in the domain of executive functions is working memory (WM) and this concept can also play a role in multitasking. The current research is based on the study of Liefooghe, Barrouillet, Vandierendonck, & Camos, (2008) on working memory and task switching cost. The current research will build upon this and will study the effect of dual-task performance on maintenance of information within WM. In order to answer this question this study will merge the Psychological Refractory Period (PRP) paradigm with a WM task. It is hypothesized that WM performance, i.e. the amount of letters recalled, decreases when performing a dual-task compared to performing a single task.

All participants of the study will be over 18 years of age including both male and female genders. Participants will be recruited via the Brunel participant pool, social media and posters. They will be invited to a cubicle room to attend a combined working memory and dual-task experiment. First, they will be informed about the study and will be asked to give written informed consent to participate in the study. Only once they have confirmed this by signing they will be given the instructions of the experiment. For the task they will be presented with visual and auditory stimuli and will have to perform two two-choice response tasks (via speeded button-presses) combined with a free-recall letter task. The dependent variables are response times and error rates. In the end, participants will be debriefed. The experiment will last approximately 1 hour. Participants will be offered £8 or course credit for participation.

Section V: Research checklist

Please answer each question by ticking the appropriate box:

Question	YES	NO
1. Does the project involve participants who are particularly vulnerable or unable to give informed consent (e.g. children/ young people under 18, people with learning disabilities, your own students)?	○	◉
2. Will the research involve people who could be deemed in any way to be vulnerable by virtue of their status within particular institutional settings (e.g., students at school, residents of nursing home, prison or other institution where individuals cannot come and go freely)?	○	◉
3. Will it be necessary for participants to take part in the study without their knowledge and consent (e.g., covert observation of people in non---public places)?	○	◉
4. Will the study involve discussion of sensitive topics (e.g., sexual activity, drug use) where participants have not given prior consent to this?	○	◉
5. Will the study involve work with participants engaged in breaking the law?	○	◉
6. Will the publications/reports resulting from the study identify participants by name or in any other way that may identify them, bring them to the attention of the authorities, or any other persons, group or faction?	○	◉
7. Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?	○	◉

	YES	NO
8. Will the study involve the use of human tissue or other human biological material?	○	●
9. Will blood or tissue samples be obtained from participants?	○	●
10. Is pain or more than mild discomfort likely to result from the study?	○	●
11. Could the study induce psychological stress or anxiety or cause harm or negative consequences beyond the risks encountered in normal life?	○	●
12. Will the study involve prolonged or repetitive testing?	○	●
13. Will financial inducements (other than reasonable expenses and compensation for time) be offered to participants?	○	●

	YES	NO
14. Will the study require the co---operation of another individual/ organisation for initial access to the groups or individuals to be recruited? If yes please attach the letters of permission from them.	○	●
15. Will you be undertaking this research as part of a work placement or in conjunction with an external organisation? If Yes and the organisation has conducted its own research ethics review, please attach the ethical approval.	○	●

If you have answered 'yes' to any of questions 1---13, you will need to complete the University Application Form for Research Ethics Approval.

Students: If you have answered 'No' to all of questions 1---13, please **sign below and submit this completed Checklist, consent form, information leaflet and any other documents and attachments for your supervisor's approval by email. Once you have received it back from your supervisor you will be able to submit via BBL. Forms that do not have your supervisor's approval will be rejected.**

Staff: If you have answered 'No' to all of questions 1---13, please **sign below and submit completed Checklist, consent form, information sheet and any other documents and attachments via BBL.**

Please note that it is your responsibility to follow the University's Code of Research Ethics and any relevant academic or professional guidelines in the conduct of your study. **This includes providing appropriate information sheets and consent forms, and ensuring confidentiality in the storage and use of data.** Any significant change in protocol over the course of the research should be notified to the Departmental Ethics Coordinator and may require a new application for ethics approval.

Applicant (Principal Investigator) Name: Pauldy Otermans
Applicant's e---signature: *Pauldy Otermans*
Date: 18 February 2015

Supervisor Section (for students only)

Please tick the appropriate boxes. The study should not be submitted until all boxes are ticked:

X	The student has read the University's [Code of Research Ethics]
X	The topic merits further research
X	The student has the skills to carry out the research
X	The consent form is appropriate
X	The participant information leaflet is appropriate
X	The procedures for recruitment and obtaining informed consent are appropriate
X	An initial risk assessment has been completed
☐	If there are issues of risk in the research, a full risk assessment has been undertaken in line with the 'School of Social Sciences Risk Assessment– FAQs' document and a risk assessment is attached.
☐	A DBS check has been obtained (where appropriate)
X	The debriefing form is appropriate (NB for psychology only --- please refer to BBL)

Any comments from supervisor:

Supervisor or module leader (where appropriate): Andre Szameitat
E---signature: *Andre Szameitat*
Date: 18 Feb 2015

Supervisors: Please **email** this form to the student who will then need to submit it and related appendices via BBL.

Student: Once you have received this form back from your supervisor, submit this completed Checklist, consent form, information sheet and any other documents and attachments via BBL.

Departmental Ethics Coordinator section:

This request for expedited review has been:	X Approved (No additional ethics form is necessary)
	Declined (Full University Ethics Form is necessary)
	Declined (Please give reason below)

Departmental Ethics Coordinator Name: Achim Schuetzwohl
E--- signature Achim Schuetzwohl
Date: 23/02/2015

Appendix 1B: Information Sheet for all experiments

Study title: **The role of executive functions in working memory and dual---tasking**

Invitation Paragraph: My name is Pauldy Otermans and I am a PhD student at the psychology department of Brunel University---London. I am conducting this study as a part of my PhD degree. This study is being supervised by Dr. Andre Szameitat (Andre.Szameitat@Brunel.ac.uk). You are being invited to take part in this research study. The department of psychology at Brunel University requires that all persons who participate in psychology studies give their written consent to do so. Please read the following and sign it if you agree.

What is the purpose of the study? The present study is aimed to explore the role of executive functions in working memory and dual---task performance.

Why have I been invited to participate? You are being invited to take part in this research because we are looking for volunteers over the age of 18 years.

Do I have to take part? No. It is up to you to decide whether or not to take part in this study. Your participation in this study is completely voluntary and you can withdraw from the study at any time.

What will happen to me if I take part and what do I have to do? You will be asked to perform a computer based working memory and dual task experiment for approximately 45 minutes. You will hear tones and see stimuli on the computer screen and you have to respond to these by button--- presses. In addition, you will be asked to memorize letters and later recall them.

What are the possible disadvantages and risks of taking part? There is no known disadvantage and/or risks of taking part in this study.

What if something goes wrong? If you have any general questions about this study, or ethical issues related to the project, you should feel free to contact Pauldy Otermans (Pauldy.otermans@brunel.ac.uk). If you have any concerns or complaints regarding the way in which the research is or has been conducted you may contact Chair of the Psychology Research Ethics Committee, Dr Achim Schuetzwohl, achim.schuetzwohl@brunel.ac.uk or Dr. Bridget Dibb Bridget.Dibb@brunel.ac.uk.

Will my taking part in this study be kept confidential? It will be assured that your responses will be kept strictly confidential. Your name will not be linked to the result of the experiment.

What will happen to the results of the research study? All data given by you will be strictly anonymous and all data will be reported by group averages and not any one individual's performance. The findings from this study will be used in one or more of the following sources; as part of my PhD thesis, scientific papers as well as presentations.

Who is organising and funding the research? The study is part of fulfilment of a PhD at Brunel University. Participants will get paid £8,--- to participate in the study which will last approximately one hour.

Who has reviewed the study? This study has been reviewed and approved by Brunel University Research Ethics Committee.

Contact for further information If you have any general questions about this project, or ethical issues relating to this project, please do not hesitate to contact Pauldy Otermans (Pauldy.otermans@brunel.ac.uk) and my supervisor Dr. Andre Szameitat (andre.szameitat@brunel.ac.uk). If you have any concerns or complaints regarding the way in which this research is or has been conducted, please feel free to contact Dr Achim Schuetzwohl, Chair of the Psychology Research Ethics Committee, at achim.schuetzwohl@brunel.ac.uk

Appendix 1C: Consent Form for all experiments

The role of executive functions in working memory and dual---tasking

	YES	NO
1. I have read the Research Participant Information Sheet.	☐	☐
2. I have had an opportunity to ask questions and discuss this study.	☐	☐
3. I understand that I am free to withdraw from the study:		
--- at any time (Please note that you will unable to withdraw once your data has been included in any reports, publications etc)	☐	☐
--- without having to give a reason for withdrawing	☐	☐
4. I understand that I will not be referred to by name in any report/publications resulting from this study	☐	☐
5. I agree to take part in this study	☐	☐

Research Participant Name:
Research Participant signature:
Date:

Principal Investigator name: Pauldy Otermans
Principal Investigator signature:
Date:

One copy to be kept by the participant and one by the researcher.

Appendix 1D: Demographics Form for all experiments

Responsible Researcher
Pauldy Otermans
PhD Student in Psychology
Brunel University
pauldy.otermans@brunel.a

Experiment The role of executive functions in working memory and dual-tasking

Experimenter ______________________________

Date & Time .______________________________.

Participant-No./ID .______________________________.

*fields marked with * are mandatory*

Your Age* ________________________

Gender* □ Female □ Male

How well do you speak and understand English? *

„not very well" – □ □ □ □ □ □ □ – *„English is my first/native language"*

Reimbursement* □ Money □ Course Credit □ None

Email *(optional)* ____

Please answer the following questions about your handedness using the responses listed:

RR = always right
R = usually right
L = usually left
LL = always left

With which hand do you:

Write ___________ Draw ___________ Throw ___________

Cut using scissors ___________ Toothbrush ___________

Cut with knife (without fork) ___________ Use a spoon ___________

Use a broom/spade (upper hand) ___________

Strike a match? ___________ Open a box (lid)? ___________

Appendix 1E: Instructions for experiment 1a

Welcome to this experiment on memory and dual-task performance.

The experiment will consist of various tasks and hence you will firstly do a practice session to become familiar with the different tasks.

There will be a memory task where you will be asked to memorize letters presented on the screen. You will have to recall these letters in a later stage of the experiment. If you do not remember a letter, press spacebar. If you are not sure about the letter, type the specific letter.
Besides the memory task, you will be asked to perform the following tasks:

The so-called auditory task consists of either a low or high pitched tone presented via speakers. When you hear the low pitched tone, press the "z" key on the computer keyboard and when you hear the high pitched tone press "x". In all tasks of the experiment, please always respond as fast and accurate as possible.

The so-called visual task consists of either a triangle or circle shown on the computer screen. When you see a triangle, press "n" and when you see the circle press "m".

Auditory task; Left Hand		Visual task; Right Hand	
Low pitched tone	**high pitched tone**	**triangle**	**circle**
Z	**X**	**N**	**M**

These tasks can be presented in two different ways: (1) either as a single task, in which only one of the stimuli is presented or (2) as a dual-task, where the stimuli will be presented simultaneously. In this latter case, you need to respond to the auditory stimulus first and only then to the visual stimulus.

All these various tasks will be practiced in the practice session.

The main experiment will only consist of combined tasks in which you will have to memorize letters, perform the single or dual tasks and then recall the letters. The tasks are presented in blocks. Before each block, there will be a written instruction on the screen informing you about the upcoming task;
For example:
"6 letters"
"Dual task"
This means that you will be asked to memorize 6 letters presented on the screen. This is followed by a dual task session. After this, you will be asked to recall the 6 letters.

Important notes

Error feedback
Please always respond as fast and as accurate as possible. You will receive an error feedback ("Error" briefly displayed at the end of the trial) in the following cases: (a) You pressed the **incorrect key(s)**, (b) you pressed the correct keys, but in the **wrong order** (e.g. first responding visual task and then the auditory one), (c) you were **too slow** with your response(s).

Don't group your responses!
In the dual-task conditions, always respond to the first task as fast as possible. Do not withhold the first response until you know the second response as well and then give both responses in brief succession. In other words, do not "group" your responses to the two tasks, but let them happen independently as soon as you are ready to respond.

Stimulus sequences are random!
Stimuli (triangle or circle; low or high pitched tone) are generated randomly on each trial. Thus, although unlikely, there may be a block in which you have e.g. 8 circles in a row.

Duration of experiment
You will first practice the task extensively for 10-15 minutes. The main experiment then takes ~30 min.

Thank you very much for your participation!

Appendix 1F: Post-questionnaire for experiment 1a

Brunel UNIVERSITY LONDON

Experiment The role of executive functions in working memory and dual-tasking

Date & Time ________________________________

Participant-ID ________________________________

In the following questionnaire we would like to ask you to answer some questions about the study you have just performed. The information will be kept confidential. If you have a question please do not hesitate to ask us immediately.

General questions about the experiment

1. Was the experiment difficult? □ Yes □ No
   If yes, please state why:
   ____

2. Was the experiment exhausting? □ Yes □ No
   If yes, please state why:
   ____

3. Do you think the experiment was overly (please tick all appropriate)
   □ difficult □ exhausting □ easy □ boring

4.Which was the most difficult task for you?

____

5. Which was the easiest task for you?

____

6. How was your concentration during the experiment?

„very high all the time“ – □ □ □ □ □ □ □ – *„very low all the time“*

7. Did you recognise anything special or strange in the experiment? □ Yes □ No
   If yes, please describe:
   ____

8. In what language do you rehearse/memorize the letters? More than 1 is possible.

Please list all the languages you know in order of dominance (native language first) and approximate age of acquisition (*i.e. the approximate age you would consider yourself to have become fluent in that language*):

List language here:	**1.**	**2.**	**3**
Age of acquisition:			

Please list what percentage of the time you are on average exposed to each language (*Your percentages should add up to 100%)*

List language here:	**1.**	**2.**	**3**
List percentage here:			

When choosing a language to speak with a person who is equally fluent in all your languages, what percentage of time would you choose to speak each language? (*Your percentages should add up to 100%*):

List language here:	**1.**	**2.**	**3**
List percentage here:			

9. Did you memorize the letters by rehearsing them in your head in other words, by repeating the letters in your head?
   □ yes □ no
   If no, please specify whether you used a specific strategy to memorize the letters and how often you used this strategy, example strategy: creating a sentence where each word starts with one of the memorized letters.

<u>Any further comments:</u>

Thank you very much for your help!

Appendix 1G: Debrief Form for all experiments

The role of executive functions in a working memory and dual-task experiment

We would like to take this opportunity to say thank you for taking your time to take part in this experiment.

Please be assured, all data collected will be treated in the strictest confidence. You are free to withdraw your data from the research at any time by contacting Pauldy.otermans@brunel.ac.uk or my supervisor Dr Andre Szameitat, Andre.Szameitat@Brunel.ac.uk .

Research has shown that usually severe decrements arise when performing two tasks at the same time compared to single task (Pashler, 1994). These decrements show as longer times to respond and/or making more errors which leads to higher demands on cognitive processes for dual-tasks as compared to single tasks (De Jong, 1995; Logan & Gordon, 2001; Luria & Meiran, 2003; Stelzel, Kraft, Brandt, & Schubert, 2008; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2005).

The goal of this study is to understand the role of executive functions in multitasking. One of the key concepts of executive functions is working memory (WM) and this concept can also play a role in multitasking. The current will study the effect of dual-task performance on maintenance of information within WM. It is hypothesized that WM performance, i.e. the amount of letters recalled, decreases when performing a dual-task compared to performing a single task. This is because dual-tasks require more attention than a single task which gives participants less time to rehearse the letters and hence performance will decrease.

If you were unduly or unexpectedly affected by taking part in the study please feel free to contact the researcher. If you feel unable for any reason what-so-ever to talk to the researcher then please either contact my supervisor (Andre.Szameitat@Brunel.ac.uk) or the ethics officers Achim.Schuetzwohl@brunel.ac.uk, and bridget.dibb@brunel.ac.uk.

The following studies, on the above topic, might be of interest to you:

Liefooghe, B., Barrouillet, P., Vandierendonck, A., & Camos, V. (2008). Working memory costs of task switching. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 34*(3), 478---494. doi: 10.1037/0278---7393.34.3.478

Pashler, H. (1994). Dual---Task Interference in Simple Tasks --- Data and Theory. *Psychological Bulletin, 116*(2), 220---244.

We would like to thank you again for your participation in this study. Please feel free to contact Pauldy Otermans, Pauldy.otermans@brunel.ac.uk via email.

Appendix 1H: Example receipts for all experiments

Project: Memory and Multitasking (Otermans/Szameitat)

Brunel UNIVERSITY LONDON

I, ___________________________________, (please print name)

confirm that I have received payment of £_______

for my participation in the above study.

Signed___________________________ Date ___________________

Appendix 1I: Instructions for experiment 1b, 4, 5 and 6

Welcome to this experiment on memory and dual-task performance.

The experiment will consist of various tasks and hence you will firstly do a practice session to become familiar with the different tasks.

There will be a memory task where you will be asked to memorize letters presented on the screen. You will have to recall these letters in a later stage of the experiment. If you do not remember a letter, press spacebar. If you are not sure about the letter, type the specific letter.
Besides the memory task, you will be asked to perform the following tasks:

The so-called auditory task consists of either a low or high pitched tone presented via speakers. When you hear the low pitched tone, press the "z" key on the computer keyboard and when you hear the high pitched tone press "x". In all tasks of the experiment, please always respond as fast and accurate as possible.

The so-called visual task consists of either a blue circle or yellow circle shown on the computer screen. When you see a blue circle, press "the left arrow key" and when you see the yellow circle press "the down arrow key".

Auditory task; Left Hand		Visual task; Right Hand	
Low pitched tone	**High pitched tone**	**Blue Circle**	**Yellow Circle**
Z	**X**	**Left Arrow**	**Down Arrow**

These tasks can be presented in two different ways: (1) either as a single task, in which only one of the stimuli is presented or (2) as a dual-task, where the stimuli will be presented simultaneously. In this latter case, you need to respond to the auditory stimulus first and only then to the visual stimulus.

All these various tasks will be practiced in the practice session.

The main experiment will only consist of combined tasks in which you will have to memorize letters, perform the single or dual tasks and then recall the letters. The tasks are presented in blocks. Before each block, there will be a written instruction on the screen informing you about the upcoming task;
For example:
"6 letters"
"Dual task"
This means that you will be asked to memorize 6 letters presented on the screen. This is followed by a dual task session. After this, you will be asked to recall the 6 letters.

Important notes

Error feedback
Please always respond as fast and as accurate as possible. You will receive an error feedback ("Error" briefly displayed at the end of the trial) in the following cases: (a) You pressed the **incorrect key(s)**, (b) you pressed the correct keys, but in the **wrong order** (e.g. first responding visual task and then the auditory one), (c) you were **too slow** with your response(s).

Feedback on performance
After each block, you will receive feedback about your performance in the single or dual task. Your speed will be shown on the screen as well as your accuracy. It is very important to have an accuracy of 80% or higher. Do not sacrifice this accuracy for the memory task. It is really important that you perform well in the single or dual task.

Don't group your responses!
In the dual-task conditions, always respond to the first task as fast as possible. Do not withhold the first response until you know the second response as well and then give both responses in brief succession. In other words, do not "group" your responses to the two tasks, but let them happen independently as soon as you are ready to respond.

Stimulus sequences are random!
Stimuli (blue or yellow circle; low or high pitched tone) are generated randomly on each trial. Thus, although unlikely, there may be a block in which you have e.g. 5 blue circles in a row.

Duration of experiment
You will first practice the task extensively for 10-15 minutes. The main experiment then takes ~30 min.

Thank you very much for your participation!

Appendix 1J: Post-Questionnaire for experiments 1b, all 2, 3, 4, 5 and 6

Brunel UNIVERSITY LONDON

Experiment The role of executive functions in working memory and dual-tasking

Date & Time ________________________________

Participant-ID ________________________________

In the following questionnaire we would like to ask you to answer some questions about the study you have just performed. The information will be kept confidential. If you have a question please do not hesitate to ask us immediately.

General questions about the experiment

5. Was the experiment difficult? □ Yes □ No
   If yes, please state why:
   ____
6. Was the experiment exhausting? □ Yes □ No
   If yes, please state why:
   ____
7. Do you think the experiment was overly (please tick all appropriate)
   □ difficult □ exhausting □ easy □ boring

8.Which was the most difficult task for you?

____

5. Which was the easiest task for you?

____

6. How was your concentration during the experiment?

„very high all the time“ – □ □ □ □ □ □ □ – *„very low all the time“*

7. Did you recognise anything special or strange in the experiment? □ Yes □ No
   If yes, please describe:
   ____

8. In what language do you rehearse/memorize the letters? More than 1 is possible.

Please list all the languages you know in order of dominance (native language first) and approximate age of acquisition (*i.e. the approximate age you would consider yourself to have become fluent in that language*):

List language here:	**1.**	**2.**	**3**
Age of acquisition:			

Please list what percentage of the time you are on average exposed to each language (*Your percentages should add up to 100%)*

List language here:	**1.**	**2.**	**3**
List percentage here:			

When choosing a language to speak with a person who is equally fluent in all your languages, what percentage of time would you choose to speak each language? (*Your percentages should add up to 100%*):

List language here:	**1.**	**2.**	**3**
List percentage here:			

9. Did you memorize the letters by rehearsing them in your head in other words, by repeating the letters in your head?

□ yes □ no

If no, please specify whether you used a specific strategy to memorize the letters and how often you used this strategy, example strategy: creating a sentence where each word starts with one of the memorized letters.

10. Are you a smoker?

□ yes □ no

If yes,

11. How many cigarettes do you smoke a day on average (the number of individual cigarettes?)

12. How long ago was your last cigarette?

13. How strong is your urge to smoke now, at the end of the experiment?

1 = No urge to smoke, 10=very strong urge to smoke, please tick appropriate box

1 □ 2 □ 3 □ 4 □ 5 □ 6 □ 7 □ 8 □ 9 □ 10 □

Any further comments:

Thank you very much for your help!

Appendix 2: Documents experiment 2

For experiment 2, a new ethics confirmation was obtained, Appendix 2A. For experiment 2, the same forms information sheet (Appendix 1B), consent form (Appendix 1C), demographics form (Appendix 1D), debrief form (Appendix 1G) and receipt (Appendix 1H) as experiment 1 were used except the instructions sheet was changed, Appendix 2B and Appendix 2C for the different experiments. Also, question 5b was added to the post-questionnaire in Appendix 1J: "5b. Which random condition was the easiest for you and why?" For Experiment 2d, question 8 was explicitly added to the post-questionnaire to see whether participants recognized the two different switch conditions: "8. Did you recognize that there were two conditions in the experiment?"

□ No □ Yes. If yes, please describe:

Appendix 2A: Ethics approval for the different experiments 2

School of Social Sciences Ethics Checklist

ETHICAL MATTERS MUST BE CONSIDERED BEFORE ANY RESEARCH TAKES PLACE
FAILURE TO FOLLOW THE CORRECT ETHICAL PROCEDURES OR CONDUCTING RESEARCH WITHOUT ETHICAL APPROVAL WHERE IT IS REQUIRED MAY LEAD TO DISCIPLINARY ACTION

Guidance

This Ethics Checklist has been designed to help determine the level of risk or harm to participants' welfare entailed in a proposed study. It also contains a sample consent form and information leaflet checklist that you can use/adapt as appropriate.

NB: If your research requires NHS ethics approval, you should not complete this form. Please provide the School with a copy of your letter of NHS approval once you receive this.

Who Completes the Checklist?

The Principal Investigator (PI) is the main researcher and can be a student. The PI (or where the PI is a student, the supervisor) is responsible for exercising appropriate professional judgement in this review.

Underpinning Codes of Ethics

Before completing this checklist, you must refer to the University Code of Research Ethics as well as the relevant code of ethics for your discipline. These are listed in the Useful Links section at the end of this guidance. It is your responsibility to follow these Codes of Research Ethics in the conduct of your study. This includes providing appropriate documentation and ensuring confidentiality in the storage and use of data (see section 3.3.2 of the University Code of Research Ethics).

The Checklist

This Checklist is in two parts:

Part 1: This must be completed by all students and staff undertaking research. This section aims to confirm that there are no ethical or risk assessment issues related to your research.

Part 2: This is for all Principal Investigators who identify that there are ethical and/or risk assessment issues in their proposed research.

YOU MUST HAVE YOUR APPLICATION, CONSENT FORM AND INFORMATION SHEET APPROVED BY YOUR DEPARTMENTAL ETHICS COORDINATOR (OR IF APPROPRIATE, UNIVERSITY ETHICS COMMITTEE) BEFORE YOU START YOUR RESEARCH AND APPROACH POTENTIAL PARTICIPANTS.

What do I have to do if I need to complete the University Research Ethics Committee Application Form?

You will need to complete and submit this via BBL. In most cases, the School will be able to review and approve the ethics form. If the research needs University level approval, your form will be submitted to the University Research Ethics Committee by the Research Office.

Risk Assessment

All Principal Investigators (and their supervisor where relevant) are required to consider matters of risk and conduct a risk assessment as part of the University's Health and Safety Policy. If issues of risk are identified, a risk assessment is required and must be attached to this form. For further information about Risk Assessments and guidance on how to undertake one, see the document 'RISK ASSESSMENT – FAQs' which can be found in in the School of Social Sciences Ethics Organisation, under my Organisations in BBL.

Disclosure and Barring Service (formerly Criminal Record Bureau) Checks

If your research involves vulnerable persons, you are required to follow University guidelines for Disclosure and Barring Service (DBS) checks. If you need a DBS check please contact the DBS Administrator in Admissions who will send you the information you need to make a DBS application.

How to submit Checklist and appendices on Blackboard Learn

Stage 1: Log into BBL

Stage 2: Click on the School of Social Sciences Research Ethics Organisation, under the My Organisations list on the right hand side

Stage 3: Download the Ethics Checklist from the folder on the homepage titled 'Research Ethics Application Form'.

Stage 3: Click on your appropriate department folder

Stage 4: Click on the Ethics Checklist Submission Assignment Tool

Stage 5: Upload your Ethics Checklist and appendices eg consent form, information leaflet, using the Browse My Computer link, and ensure you have uploaded the correct documents

Stage 6: Once you have confirmed they are the correct documents, click submit

Stage 7: You will receive an email receipt of your submission to your Brunel email account

Stage 8: Click on the My Grades link in the School of Social Sciences Research Ethics Organisation to find the outcome and feedback once it has been reviewed by your Departmental Ethics Coordinator.

Further information about how to submit is available in the School of Social Sciences Ethics Organisation, under My Organisations, in BBL.

What happens after I have received ethical approval?

Once you have received ethical approval, you can start your research.

Students are required to retain a copy of the approved Checklist, consent form and information leaflet and submit these with their research report/dissertation/thesis.

All undergraduate and postgraduate work submitted/conducted without ethical approval may be subject to academic penalties and disciplinary action.

If your research is delayed and will extend beyond the dates stated on your form, please contact your Departmental Ethics Coordinator to seek approval for an extension.

Useful Links and Resources
University Research Code of Ethics LINK
UREC website - LINK
Code of Ethics – Anthropology LINK
Code of Ethics – Economics and Finance (Use University Research Code of Ethics)
Code of Ethics – Politics and History (Use University Research Code of Ethics)
Code of Human Research Ethics – Psychology PDF
Code of Ethics – Sociology and Communications - LINK

Risk Assessment – FAQs – School of Social Sciences Ethics Organisation, under my Organisations in BBL.

Contacts

Anthropology Ethics Coordinator:	Dr Isak Niehaus
Economics and Finance Ethics Coordinator:	Professor Frank Skinner
Politics and History Ethics Coordinator:	Dr John MacMillan
Psychology Ethics Coordinator:	Dr Achim Schutzwohl/ Dr Bridget Dibb
Sociology and Communications Ethics Coordinator:	Dr Simon Weaver

Research Ethics Administrator: Ms Amreen Malik

SSS Research Ethics Review Checklist – Part 1

Section I: Project details

1. Project title: The role of executive functions in working memory and dual-tasking	
2. Proposed start date: 05/08/2015	3. Proposed end date: 31/08/2017

Section II: Applicant details

4. Name of researcher (applicant)	Pauldy Otermans
5. Student Number	1429594
6. Status	PGR Student
7. Department	Psychology
8. Brunel e-mail address	Pauldy.otermans@brunel.ac.uk

9. Telephone number	07518225153

Section III: For students only

10. Module name and number:	Psychology PhD
11. Supervisor's name:	Andre Szameitat
12. Brunel supervisor's e-mail address:	Andre.szameitat@brunel.ac.uk

	Yes	No
13. Does this research involve human participants?	◉	○
14. Does this research raise any ethical or risk concerns as set out in the University Code of Research Ethics or relevant disciplinary code?	○	◉
15. Risk Assessment – are there any elements of risk related to the proposed research? (See Risk Assessment – FAQs)	○	◉

If you have answered **Yes** to any of questions 13-15, you must **complete Part 2** of this form.

Students: If you have answered No, please email this document to your supervisor who will confirm that the research does not involve ethical issues. Once electronically signed by your supervisor, please submit Part 1 of this form via BBL within 1 week. Please keep a copy for yourself and bind it into your dissertation/thesis as an appendix.

Staff: If you have answered No, please sign below and submit your form via BBL. Please keep a copy for yourself.

If your research methodology changes significantly, you must submit a new form.

For Supervisor's/Staff e- signature

I confirm that there are no ethical or risk issues relating to this research and the applicant can proceed with the proposed research.
e-signature/ Date:

SSS Research Ethics Review Checklist – Part 2

Section IV: Description of project

Please provide a short description of your project:

The aim of this study is to understand the role of executive functions in multitasking. One of the key theoretical concepts in the domain of executive functions is working memory (WM) and this concept can also play a role in multitasking. The current research is based on the study of (Liefooghe et al., 2008) on working memory and task switching cost. The current research will build upon this and will study the effect of dual-task performance on maintenance of information within WM. In order to answer this question this study will merge the Psychological Refractory Period (PRP) paradigm with a WM task. It is hypothesized that WM performance, i.e. the amount of letters recalled, decreases when performing a dual-task compared to performing a single task. However, there are many differences between pure single task and pure dual-task blocks. The aim is to show that a difference in recall performance can be found by different manipulations to the experimental paradigm. This means that the task block conditions will differ in difficulty, i.e. the amount of time they demand executive functions. Therefore, several parameters of the experiment, for instance, the temporal offset between stimuli and the order of stimulus presentation will be varied. The prediction is that recall of letters will decrease when the order of the dual-task block is varied compared to when this order is fixed. Furthermore, recall performance will be poorer when more switches in order presentation are presented. The role of a variable temporal offset between stimuli is so far unresolved and remains an open question. Accordingly, the aim of this manipulation is to get a better understanding of the role of the variable stimulus offset on recall performance and to what extent executive functions are needed. All participants of the study will be over 18 years of age including both male and female genders. Participants will be recruited via the Brunel participant pool, social media and posters. They will be invited to a cubicle room to attend a combined working memory and dual-task experiment. First, they will be informed about the study and will be asked to give written informed consent to participate in the study. Only once they have confirmed this by signing they will be given the instructions of the experiment. For the task they will be presented with visual and auditory stimuli and will have to perform two two-choice response tasks (via speeded button-presses) combined with a free-recall letter task. The dependent variables are response times and error rates. In the end, participants will be debriefed. The experiment will last approximately 1 hour. Participants will be offered £8 or course credit for participation.

Section V: Research checklist

Please answer each question by ticking the appropriate box:

	YES	NO
1. Does the project involve participants who are particularly vulnerable or unable to give informed consent (e.g. children/ young people under 18, people with learning disabilities, your own students)?	○	◉

	YES	NO
2. Will the research involve people who could be deemed in any way to be vulnerable by virtue of their status within particular institutional settings (e.g., students at school, residents of nursing home, prison or other institution where individuals cannot come and go freely)?	○	◉
3. Will it be necessary for participants to take part in the study without their knowledge and consent (e.g., covert observation of people in non-public places)?	○	◉
4. Will the study involve discussion of sensitive topics (e.g., sexual activity, drug use) where participants have not given prior consent to this?	○	◉
5. Will the study involve work with participants engaged in breaking the law?	○	◉
6. Will the publications/reports resulting from the study identify participants by name or in any other way that may identify them, bring them to the attention of the authorities, or any other persons, group or faction?	○	◉
7. Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?	○	◉
8. Will the study involve the use of human tissue or other human biological material?	○	◉
9. Will blood or tissue samples be obtained from participants?	○	◉
10. Is pain or more than mild discomfort likely to result from the study?	○	◉
11. Could the study induce psychological stress or anxiety or cause harm or negative consequences beyond the risks encountered in normal life?	○	◉
12. Will the study involve prolonged or repetitive testing?	○	◉
13. Will financial inducements (other than reasonable expenses and compensation for time) be offered to participants?	○	◉

	YES	NO
14. Will the study require the co-operation of another individual/ organisation for initial access to the groups or individuals to be recruited? If yes please attach the letters of permission from them.	○	◉
15. Will you be undertaking this research as part of a work placement or in conjunction with an external organisation? If Yes and the organisation has conducted its own research ethics review, please attach the ethical approval.	○	◉

If you have answered 'yes' to any of questions 1-13, you will need to complete the University Application Form for Research Ethics Approval.

Students: If you have answered 'No' to all of questions 1-13, please **sign below and submit this completed Checklist, consent form, information leaflet and any other documents and attachments for your supervisor's approval by email. Once you have received it back from your supervisor you will be able to submit via BBL. Forms that do not have your supervisor's approval will be rejected.**

Staff: If you have answered 'No' to all of questions 1-13, please **sign below and submit this completed Checklist, consent form, information sheet and any other documents and attachments via BBL.**

Please note that it is your responsibility to follow the University's Code of Research Ethics and any relevant academic or professional guidelines in the conduct of your study. **This includes providing appropriate information sheets and consent forms, and ensuring confidentiality in the storage and use of data.** Any significant change in protocol over the course of the research should be notified to the Departmental Ethics Coordinator and may require a new application for ethics approval.

Applicant (Principal Investigator) Name: Pauldy Otermans
Applicant's e-signature: *Pauldy Otermans*
Date: 5th August 2015

Supervisor Section (for students only)

Please tick the appropriate boxes. The study should not be submitted until all boxes are ticked:

☒	The student has read the University's Code of Research Ethics
☒	The topic merits further research
☒	The student has the skills to carry out the research
☒	The consent form is appropriate
☒	The participant information leaflet is appropriate
☒	The procedures for recruitment and obtaining informed consent are appropriate
☒	An initial risk assessment has been completed
☐	If there are issues of risk in the research, a full risk assessment has been undertaken in line with the 'School of Social Sciences Risk Assessment– FAQs' document and a risk assessment is attached.
☐	A DBS check has been obtained (where appropriate)

X	The debriefing form is appropriate (NB for psychology only - please refer to BBL)

Any comments from supervisor:

Supervisor or module leader (where appropriate): Andre Szameitat
E-signature: *Andre Szameitat*
Date: 5th August 2015

Supervisors: Please **email** this form to the student who will then need to submit it and related appendices via BBL.

Student: Once you have received this form back from your supervisor, submit this completed Checklist, consent form, information sheet and any other documents and attachments via BBL.**Departmental Ethics Coordinator section:**

This request for expedited review has been:

☐ Approved (No additional ethics form is necessary)

☐ Declined (Full University Ethics Form is necessary)

☐ Declined (Please give reason below)

Departmental Ethics Coordinator Name:
E- signature
Date:

Appendix 2B: Instructions for experiment 2a

Welcome to this experiment on memory and dual-task performance.

The experiment will consist of various tasks and hence you will first do a practice session to become familiar with the different tasks.
There will be a memory task where you will be asked to memorize letters presented on the screen. You will have to recall these letters in a later stage of the experiment. If you do not remember a letter, please press the spacebar. If you are not sure about the letter, you can give a guess.

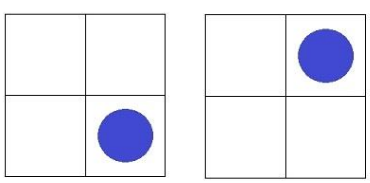
Besides the memory task, you will be asked to perform the following tasks:

The so-called *auditory task* consists of either a low or high pitched tone presented via speakers. When you hear the low pitched tone, press the “z” key on the computer keyboard and when you hear the high pitched tone press “x”. In all tasks of the experiment, please always respond as fast and accurate as possible.

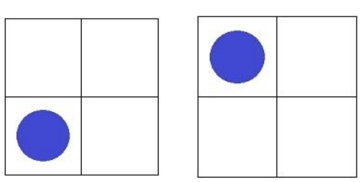
The so-called *visual task* consists of either a blue circle or yellow circle shown on the computer screen. When you see a blue circle, press “the left arrow key” and when you see the yellow circle press “the down arrow key”.

Auditory task; Left Hand		Visual task; Right Hand	
Low pitched tone	**High pitched tone**	**Blue Circle**	**Yellow Circle**
Z	**X**	**Left Arrow**	**Down Arrow**

These tasks will be presented as a dual-task, where the stimuli will be presented simultaneously. The position of the circle determines the order in which you need to respond to the stimuli. If the circle appears on the right part of the square you have to respond to the auditory stimulus first and only then to the visual stimulus:



If the circle appears on the left part of the square you have to respond to the visual stimulus first and only then to the auditory stimulus:



All these various tasks will be practiced in the practice session. The main experiment will only consist of combined tasks in which you will have to memorize letters, perform the dual task and then recall the letters. The tasks are presented in blocks.

Important notes

Error feedback
Please always respond as fast and as accurate as possible. You will receive an error feedback ("**Error**" briefly displayed at the end of the trial) in the following cases: (a) You pressed the **incorrect key(s)**, (b) you pressed the correct keys, but in the **wrong order**, (c) you were **too slow** with your response(s).

Feedback on performance
After each block, you will receive feedback about your performance in the dual task. Your speed will be shown on the screen as well as your accuracy. It is very important to have an accuracy of 80% or higher. Do not sacrifice this accuracy for the memory task. It is really important that you perform well in the dual task.

Don't group your responses!
In the dual-task conditions, always respond to the first task as fast as possible. Do not withhold the first response until you know the second response as well and then give both responses in brief succession. In other words, do not "group" your responses to the two tasks, but let them happen independently as soon as you are ready to respond.

Stimulus sequences are random!
Stimuli (blue or yellow circle; low or high pitched tone) are generated randomly on each trial. Thus, although unlikely, there may be a block in which you have e.g. 6 blue circles in a row.

Duration of experiment
You will first practice the task extensively for 10-15 minutes. The main experiment then takes ~30 min.

Thank you very much for your participation!

Appendix 2C: Instructions for experiment 2b

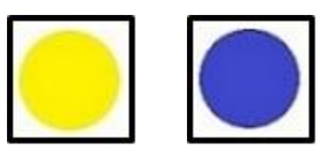
Welcome to this experiment on memory and dual-task performance.
The experiment will consist of various tasks and hence you will first do a practice session to become familiar with the different tasks.
There will be a memory task where you will be asked to memorize letters presented on the screen. You will have to recall these letters in a later stage of the experiment. If you do not remember a letter, please press the spacebar. If you are not sure about the letter, you can give a guess.

Besides the memory task, you will be asked to perform the following tasks:
The so-called *auditory task* consists of either a low or high pitched tone presented via speakers. When you hear the low pitched tone, press the “z” key on the computer keyboard and when you hear the high pitched tone press “x”. In all tasks of the experiment, please always respond as fast and accurate as possible.

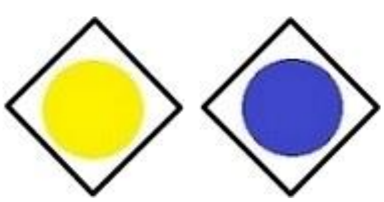
The so-called *visual task* consists of either a blue circle or yellow circle shown on the computer screen. When you see a blue circle, press “the left arrow key” and when you see the yellow circle press “the down arrow key”.

Auditory task; Left Hand		Visual task; Right Hand	
Low pitched tone	**High pitched tone**	**Blue Circle**	**Yellow Circle**
Z	**X**	**Left Arrow**	**Down Arrow**

These tasks will be presented as a dual-task, where the stimuli will be presented simultaneously. The cue around the circle determines the order in which you need to respond to the stimuli.
If there is a square around the circle, you first have to respond to the tone and then to the colour of the circle:



If there is a diamond around the circle, you first have to respond to the colour of the circle and then to the tone:



All these various tasks will be practiced in the practice session.
The main experiment will only consist of combined tasks in which you will have to memorize letters, perform the dual task and then recall the letters. The tasks are presented in blocks.

Important notes

Error feedback
Please always respond as fast and as accurate as possible. You will receive an error feedback ("**Error**" briefly displayed at the end of the trial) in the following cases: (a) You pressed the **incorrect key(s)**, (b) you pressed the correct keys, but in the **wrong order**, (c) you were **too slow** with your response(s).

Feedback on performance
After each block, you will receive feedback about your performance in the dual task. Your speed will be shown on the screen as well as your accuracy. It is very important to have an accuracy of 80% or higher. Do not sacrifice this accuracy for the memory task. It is really important that you perform well in the dual task.

Don't group your responses!
In the dual-task conditions, always respond to the first task as fast as possible. Do not withhold the first response until you know the second response as well and then give both responses in brief succession. In other words, do not "group" your responses to the two tasks, but let them happen independently as soon as you are ready to respond.

Stimulus sequences are random!
Stimuli (blue or yellow circle; low or high pitched tone) are generated randomly on each trial. Thus, although unlikely, there may be a block in which you have e.g. 6 blue circles in a row.

Duration of experiment
You will first practice the task extensively for 20-25 minutes. The main experiment then takes ~20 min.

Thank you very much for your participation!

Appendix 3: Documents experiment 3

Experiment 3 was part of the ethics confirmation of Experiment 2, Appendix 2A. For experiment 3, the same forms (information sheet (Appendix 1B), consent form (Appendix 1C), demographics form (Appendix 1D), debrief form (Appendix 1G) and receipt (Appendix 1H) as experiment 1a and the post-questionnaire of experiment 1b was used (Appendix 1J) were used. The instructions sheet was changed, Appendix 3A.

Appendix 3A: Instructions for experiment 3

Welcome to this experiment on memory and dual-task performance.

The experiment will consist of various tasks and hence you will first do a practice session to become familiar with the different tasks.

There will be a memory task where you will be asked to memorize letters presented on the screen. You will have to recall these letters in a later stage of the experiment. If you do not remember a letter, please press the spacebar. If you are not sure about the letter, you can give a guess.

Besides the memory task, you will be asked to perform the following tasks:

The so-called *auditory task* consists of either a low or high pitched tone presented via speakers. When you hear the low pitched tone, press the "z" key on the computer keyboard and when you hear the high pitched tone press "x". In all tasks of the experiment, please always respond as fast and accurate as possible.

The so-called *visual task* consists of either a blue circle or yellow circle shown on the computer screen. When you see a blue circle, press "the left arrow key" and when you see the yellow circle press "the down arrow key".

Auditory task; Left Hand		Visual task; Right Hand	
Low pitched tone	**High pitched tone**	**Blue Circle**	**Yellow Circle**
Z	**X**	**Left Arrow**	**Down Arrow**

These tasks will be presented as a dual-task, where the stimuli will be presented simultaneously. The time between the presentation of the auditory stimulus and the visual stimulus will vary. You need to respond to the auditory stimulus first and only then to the visual stimulus.

All these various tasks will be practiced in the practice session.

The main experiment will only consist of combined tasks in which you will have to memorize letters, perform the dual task and then recall the letters. The tasks are presented in blocks.

Important notes

Error feedback
Please always respond as fast and as accurate as possible. You will receive an error feedback ("Error" briefly displayed at the end of the trial) in the following cases: (a) You pressed the **incorrect key(s)**, (b) you pressed the correct keys, but in the **wrong order** (e.g. first responding visual task and then the auditory one), (c) you were **too slow** with your response(s).

Feedback on performance
After each block, you will receive feedback about your performance in the dual task. Your speed will be shown on the screen as well as your accuracy. It is very important to have an accuracy of 80% or higher. Do not sacrifice this accuracy for the memory task. It is really important that you perform well in the dual task.

Don't group your responses!
In the dual-task conditions, always respond to the first task as fast as possible. Do not withhold the first response until you know the second response as well and then give both responses in brief succession. In other words, do not "group" your responses to the two tasks, but let them happen independently as soon as you are ready to respond.

Stimulus sequences are random!
Stimuli (blue or yellow circle; low or high pitched tone) are generated randomly on each trial. Thus, although unlikely, there may be a block in which you have e.g. 6 blue circles in a row.

Duration of experiment
You will first practice the task extensively for 10-15 minutes. The main experiment then takes ~30 min.

Thank you very much for your participation!

Appendix 4: Time on Task analyses

This appendix describes the results of the time on task analyses performed on the behavioural experiments described in Chapter 2 and 3.

Experiment 1b (PRP dual-task with single and dual-task, memory load of 5, 6, and 7 letters). Time on task, as before, is defined as the time from the onset of the first stimulus until the response to the second stimulus. For the dual-task processing task this means time on task is the time from the presentation of the auditory stimulus until the response to the visual stimulus. In the single task it is defined as the overall response time. A 2 (Processing task) x 3 (Memory load) repeated-measures ANOVA was conducted to test whether the time on task for the different tasks and loads varied. The main effect of task was significant, $F(1,21) = 644.00$, $p<0.001$. Time on task was significantly longer in the dual-task condition (1136 ± 162 ms) as compared to the single task (554 ± 77 ms) for all memory loads, all $t(21) > 20.14$, $p < 0.001$. Participants spend more than twice as much time completing the dual-task as compared with the single task, which leads to less time being available to rehearse the letters in the dual-task condition. The main effect of load was not significant, $F(2,42) = 1.54$, $p = 0.23$ indicating that the differences in time on task between the different memory loads was not significant. The interaction effect between task and load was not significant, $F(2,42) = 1.02$, $p = 0.37$.

Experiment 2c (PRP dual-task with fixed and random order, memory load of 6 letters). Participants spend significantly more time on task in the random condition (1631 ± 193 ms) as compared to the fixed condition (1304 ± 163 ms), $t(16) = 9.85$, $p < 0.001$. This means that participants had less time in the random condition for memory rehearsal leading to lower memory performance.

Experiment 2e (PRP dual-task with low (2) and high (9) switches in the random order condition, memory load of 6 letters). Participants spend significantly more time on task in the high switches condition (1768 ± 233 ms) as compared to the low switches condition (1665 ± 199 ms), $t(32) = 5.42$, $p < 0.001$. This means that participants had less time in the high switch condition for memory rehearsal leading to lower memory performance.

Appendix 5: Documents experiment 4a (pilot for fMRI 1)

For experiment 4a, the ethics form fell under the ethics approval of experiment 2 (Appendix 2A). For experiment 4a, the same forms, information sheet (Appendix 1B), consent form (Appendix 1C), demographics form (Appendix 1D), instructions (Appendix 1I), post-questionnaire (Appendix 1J) and debrief form (Appendix 1G) as previous experiments were used.

Appendix 6: Documents experiment 4b, fMRI study 1

For experiment 4b, a new ethics approval was obtained (Appendix 5A). For experiment 4b, the same forms, information sheet (Appendix 1B), consent form (Appendix 1C), demographics form (Appendix 1D), instructions (Appendix 1I), post-questionnaire (Appendix 1J), debrief form (Appendix 1G) and receipts (Appendix 1H) as previous experiments were used. Furthermore, since experiment 4b was an fMRI study, several more forms were used. These contained a MRI information sheet (Appendix 5B), a MRI consent form (Appendix 5C), a MRI initial screening form (Appendix 5D) and a MRI second screening form (Appendix 5E).

Appendix 6A: Ethics approval for experiment 4b

College of Health and Life Sciences Research Ethics Committee (DLS)
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

5 July 2016

LETTER OF APPROVAL

Applicant: Miss Pauldy Otermans

Project Title: The role of working memory in dual-task performance, an fMRI study

Reference: 2942-MHR-Jul/2016- 3329-2

Dear Miss Pauldy Otermans

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.

Please note that:

- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to receipt by the Committee of satisfactory responses to any conditions that may appear above, in addition to any subsequent changes to the protocol.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the studyYou may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Professor Christina Victor

Chair

College of Health and Life Sciences Research Ethics Committee (DLS)
Brunel University London

Page 1 of 1

Appendix 6B: MRI Information Sheet

ROYAL HOLLOWAY, UNIVERSITY OF LONDON - MAGNETIC RESONANCE IMAGING UNIT

INFORMATION FORM - ADULTS

These notes give some information about an (f)MRI study in which you are invited to take part. FMRI is a method for producing images of the activity in the brain as people carry out various mental tasks. It involves placing the participant inside a large, powerful magnet which forms part of the brain scanner. When particular regions of the brain are active, they require more oxygen, which comes from red corpuscles in the blood. As a result, the flow of blood increases. This can be detected as changes in the echoes from brief pulses of radio waves. These changes can then be converted by a computer into 3D images. This enables us to determine which parts of the brain are active during different tasks. MRI is a method for producing images of the grey and white matter of the brain. This is made possible due to the fact that regions containing gray or white matter have different effects on the echoes from brief pulses of radio waves, which we can visualize as 3D images.

DTI is a method for visualizing anatomical connections between different brain regions. This is made possible due to the fact that water molecules tend to move along a major direction in areas that are part of a fibre bundle, whereas they tend to move in random directions outside such fibre bundles. This difference can be visualized in 3D images.

MRS is a method for measuring the amount of certain metabolites (e.g. GABA) in a specific region of the brain. This is made possible by the fact that different metabolites have different effects on the echoes from brief pulses of radio waves, and these differences can be measured.

In a typical experiment, you may be scanned with just one or a combination of the methods described above. As far as we know, this procedure poses no direct health risks. However, the Department of Health advises that certain people should NOT be scanned. Because the scanner magnet is very powerful, it can interfere with heart pacemakers and clips or other metal items which have been implanted into the body by a surgeon, or with body-piercing items. If you have had surgery which may have involved the use of metal items you should NOT take part. Note that only ferro-magnetic materials (e.g. steel) are likely to cause significant problems. Thus normal dental amalgam fillings do not prohibit you from being scanned, though a dental plate which contained metal would do so, and you would be asked to remove it. You will be asked to remove metal from your pockets (coins, keys), remove articles of clothing which have metal fasteners (belts, bras, etc.), as well as most jewellery. Alternative clothing will be provided as necessary. Watches and credit cards should not be taken into the scanner since it can interfere with their operation. You will be asked to complete a questionnaire (the Initial Screening Form) which asks about these and other matters to determine whether it is safe for you to be scanned. In addition, you are asked to give the name and address of your Family Doctor. This is because there is a very small chance that the scan could reveal something which required investigation by a doctor. If that happened, we would contact your doctor directly. By signing the consent form, you authorise us to do this. You will also be asked to complete a second, shorter, screening form immediately before the scan.

To be scanned, you would lie on your back on a narrow bed on runners, on which you would be moved until your head was inside the magnet. This is rather like having your head put inside the drum of a very large front-loading washing machine. The scanning process itself creates intermittent loud noises, and you would wear ear-plugs or sound-attenuating headphones. We would be able to talk to you while you are in the scanner through an intercom. If you are likely to become very uneasy in this relatively confined space (suffer from claustrophobia), you should NOT take part in the study. If you do take part and this happens, you will be able to alert the experimenters by activating an alarm and will then be removed from the scanner quickly. It is important that you keep your head as still as possible during the scan, and to help you with this, your head will be partially restrained with padded headrests. We shall ask you to relax your head and keep it still for a period that depends on the experiment but may be more than one hour, which may require some effort on your part. If this becomes unacceptably difficult or uncomfortable, you may demand to be removed from the scanner.

You may be asked to look at a screen through a small mirror (or other optical device) placed just above your eyes and/or be asked to listen to sounds through headphones. You may be asked to make judgements about what you see or asked to perform some other kind of mental task. Details of the specific experiment in which you are invited to participate will either be appended to this sheet or else given to you verbally by the experimenter. Detailed instructions will be given just before the scan, and from time to time during it.

The whole procedure will typically take about 1 hour, plus another 15 minutes to discuss with you the purposes of the study and answer any questions about it which you may raise. You will be able to say that you wish to stop the testing and leave at any time, without giving a reason. This would not affect your relationship with the experimenters in any way. The study will not benefit you directly, and does not form part of any medical diagnosis or treatment. If you agree to participate you will be asked to sign the initial screening form that accompanies this information sheet, in the presence of the experimenter (or other witness, who should countersign the form giving their name and address, if this is not practical). It is perfectly in order for you to take time to consider whether to participate, or discuss the study with other people, before signing. After signing, you will still have the right to withdraw at any time before or during the experiment, without giving a reason.

The images of your brain will be held securely and you will not be identified by name in any publications that might arise from the study. We may share your data with carefully chosen research colleagues, or with big databases such as the UK Data Archive, but the information we share will never contain your name or address. The information in the two screening forms will also be treated as strictly confidential and the forms will be held securely until eventually destroyed.

Further information about the specific study in which you are invited to participate may have been appended overleaf, if the experimenter has felt that this would be helpful. Otherwise, he/she will already have told you about the study and will give full instructions prior to the scan. Please feel free to ask any questions about any aspect of the study or the scanning procedure before completing the initial screening form.

Appendix 6C: MRI Consent Form

ROYAL HOLLOWAY, UNIVERSITY OF LONDON - MAGNETIC RESONANCE IMAGING UNIT

CONSENT FORM

NAME OF PARTICIPANT…………………………………………………

Please read the following statement carefully and then add your signature. If you have any questions, please ask the person who gave you this form. You are under no pressure to give your consent and you are free to withdraw from the MRI examination at any time.

I agree to participate in an MRI examination conducted for research purposes

by …………………………………………………. (name of researcher)

on ………………………………………………….(name of project).

I understand that the examination is not part of any medical treatment.

I have completed two screening forms and I have been given an opportunity to discuss any issues arising from them.

The nature of the examination has been explained to me and I have had an opportunity to ask questions about it.

I consent to my UK general practitioner being contacted in the unlikely event that the scan reveals any suspected abnormality.

Signature …………………………………….. Date………………………..

(for children under 18 years: signature by child and a parent or guardian)

WITNESS:

Statement by a witness, who must be either an authorised person or a scientific collaborator who is familiar with the experimental procedure and is able to answer questions about it.

I certify that the above participant signed this form in my presence. I am satisfied that the participant fully understands the statement made and I certify that he/she had adequate opportunity to ask questions about the procedure before signing.

Signature………………………………………. Date………………………..

Name ……………………………….

Address of witness (if not an Authorised Person):

Appendix 6D: MRI Initial Screening Form

ROYAL HOLLOWAY, UNIVERSITY OF LONDON - MAGNETIC RESONANCE IMAGING UNIT

INITIAL SCREENING FORM

NAME OF PARTICIPANT ………………………………………………. Sex: M / F

Date of birth……………………… Approximate weight in kg…… Approximate height in cm…….

Please read the following questions CAREFULLY and provide answers. For a very small number of individuals, being scanned can endanger comfort, health or even life. The purpose of these questions is to make sure that you are not such a person. You have the right to withdraw from the screening and subsequent scanning if you find the questions unacceptably intrusive. The information you provide will be treated as strictly confidential and will be held in secure conditions.

Delete as appropriate

1. Have you been fitted with a pacemaker or artificial heart valve? YES/NO
2. Have you any aneurysm clips, shunts or stents in your body or a cochlear implant? YES/NO
3. Have you ever had any metal fragments in your eyes? YES/NO
4. Have you ever had any metal fragments, e.g. shrapnel in any other part of your body? YES/NO
5. Have you any surgically implanted metal in any part of your body, other than dental fillings and crowns (e.g. joint replacement or bone reconstruction) YES/NO
6. Have you ever had any surgery that might have involved metal implants of which you are not aware? YES/NO
7. Do you wear a denture plate or brace with metal in it? YES/NO
8. Do you wear a hearing aid? YES/NO
9. Do you use drug patches attached to your skin? YES/NO
10. Have you ever suffered from any of: epilepsy, diabetes or thermoregulatory problems? YES/NO
11. Have you ever suffered from any heart disease? YES/NO
12. Is there any possibility that you might be pregnant? YES/NO
13. Have you been sterilised using clips? YES/NO
14. Do you have a contraceptive coil (IUD) or other contraceptive implants installed? YES/NO

    If yes, please provide details: ____
15. Are you currently breast-feeding an infant? YES/NO

Please enter below the name and address of your UK doctor (general practitioner).

I have read and understood the questions above and have answered them correctly.

SIGNED………………………………… DATE…………………………

(for children under 18 years: signature by a parent or guardian)

In the presence of ………………………………….. (name) …………………………………..(signature)

Address of witness, if not the experimenter:

Appendix 6E: Second Screening Form

ROYAL HOLLOWAY, UNIVERSITY OF LONDON - MAGNETIC RESONANCE IMAGING UNIT

SECOND SCREENING FORM

This form should be completed and signed immediately before your scan, after removal of any jewellery or other metal objects and (if required by the operator) changing your clothes.

NAME OF PARTICIPANT ………………………………………………

Date of birth……………………………… Sex: M / F

Please read the following questions CAREFULLY and provide answers. For a very small number of individuals, being scanned can endanger comfort, health or even life. The purpose of these questions is to make sure that you are not such a person.

You have the right to withdraw from the screening and subsequent scanning if you find the questions unacceptably intrusive. The information you provide will be treated as strictly confidential and will he held in secure conditions.

BEFORE YOU ARE TAKEN THROUGH FOR YOUR SCAN IT IS ESSENTIAL THAT YOU REMOVE **ALL METAL OBJECTS** INCLUDING:-WATCHES, PENS, LOOSE CHANGE, KEYS, HAIR CLIPS, ALL JEWELLERY, METALLIC COSMETICS, CHEQUE/CASH POINT CARDS.

	Delete as appropriate
1. Are you wearing or carrying any metal items such as those listed above?	YES/NO
2. Have your answers to any of the questions in the initial screening form changed?	
(The initial screening form must be shown to you before you answer this question.)	YES/NO
Specifically, please confirm:	
3. Have you been fitted with a pacemaker, artificial heart valve or cochlear implant?	YES/NO
4. Are you wearing a drug patch attached to your skin?	YES/NO
5. Is there any possibility that you might be pregnant?	YES/NO

I have read and understood the questions above and have answered them correctly.

SIGNATURE………………………………… DATE…………………………

(for children under 18 years: signature by a parent or guardian)

FOR STAFF USE:

I certify that the initial screening form and the consent form have been completed by the person named above and I have attached them to this form. The volunteer has been given the standard information sheet about MRI experiments, together with any necessary study-specific information, and has been given an opportunity to ask questions. I am satisfied that the volunteer is adequately informed and understands the content of the consent form. I have taken adequate steps to ensure that the volunteer has no ferro-magnetic metal in or on his/her person and I am satisfied that the scan can proceed.

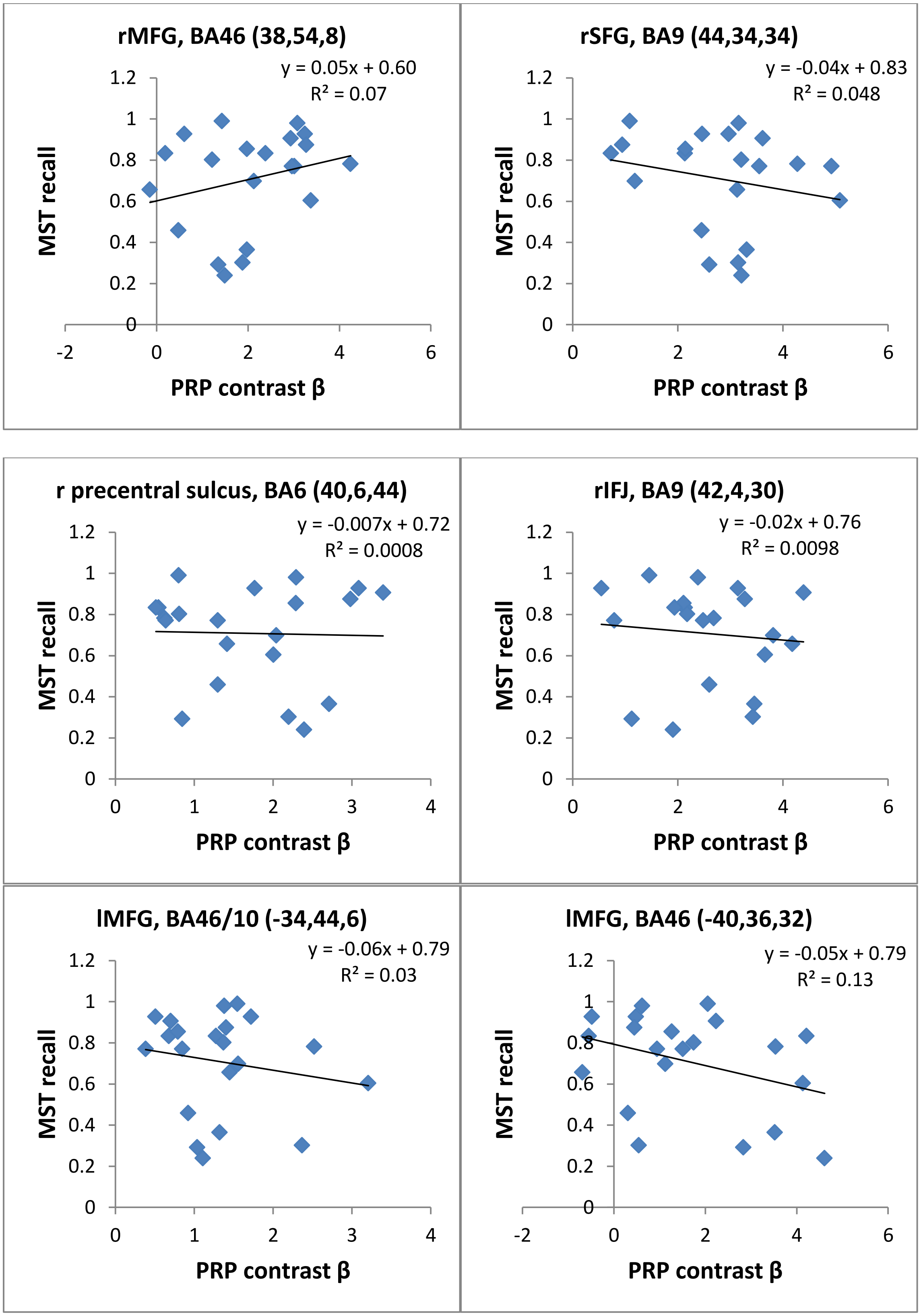
SIGNATURE………………………………… NAME (print) …………………………………..

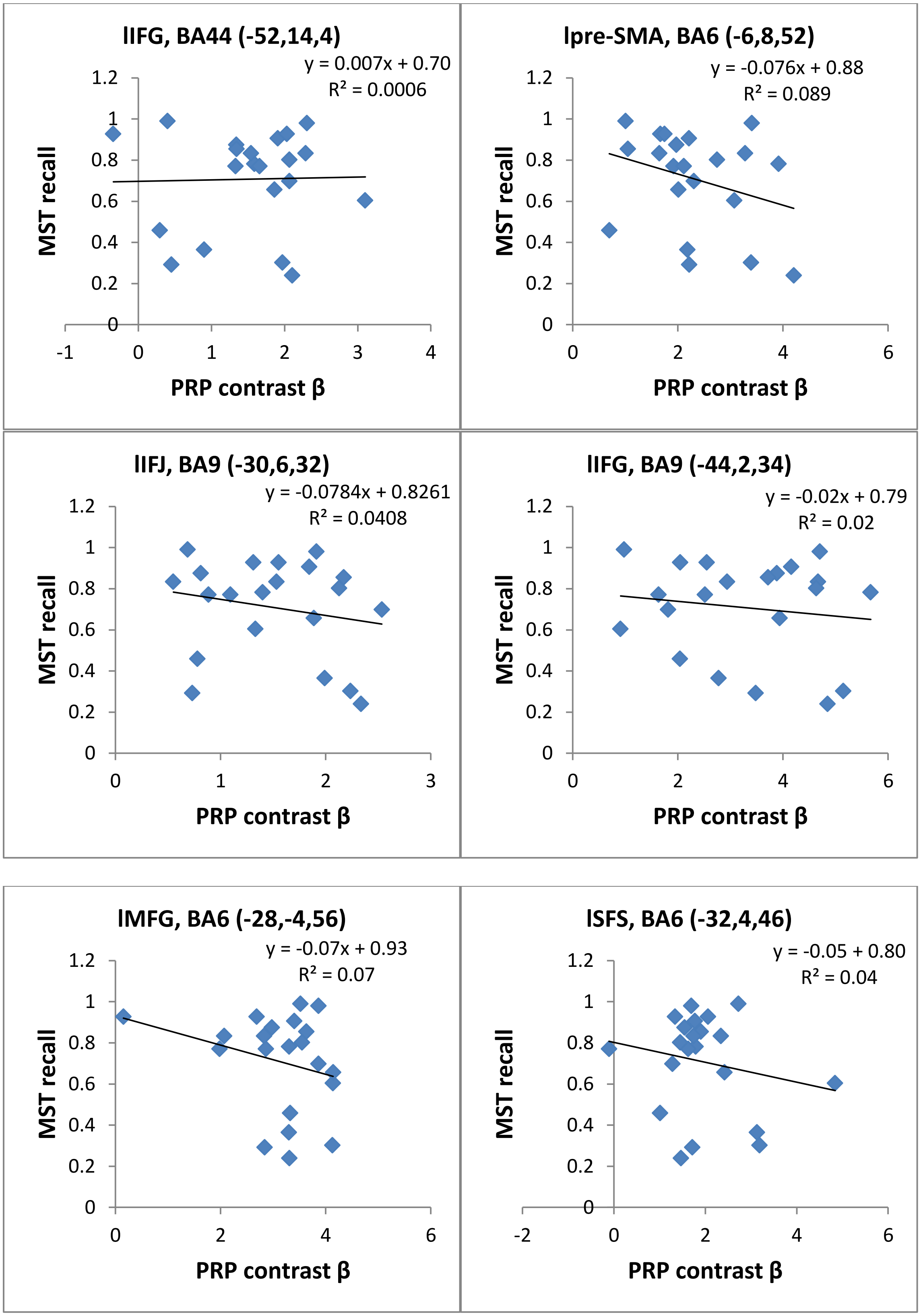
Appendix 7: Supplementary material experiment 4b, fMRI study 1

Appendix 7A: Scatterplots showing the correlation between the brain activity in PRP and the behavioural performance in WM for the other 13 peaks

Table A.0.1: Results of Pearson's correlations between the beta values of the PRP contrast and the recall performance in the MST condition for the other 13 peaks.

Peak	r	R^2	p
(38,54,8)	0.255	0.065	0.132
(44,34,34)	-0.221	0.049	0.168
(40,6,44)	-0.028	0.0008	0.452
(42,4,30)	-0.099	0.010	0.335
(-34,44,6)	-0.180	0.032	0.218
(-40,36,32)	-0.354	0.125	0.058
(-52,14,4)	0.024	0.0006	0.459
(-6,8,52)	-0.298	0.089	0.095
(-30,6,32)	-0.202	0.041	0.190
(-44,2,34)	-0.140	0.020	0.273
(-28,-4,56)	-0.271	0.074	0.117
(-32,-4,46)	-0.198	0.039	0.195
(-22,-10,50)	-0.302	0.091	0.092


rMFG, BA46 (38,54,8)
y = 0.05x + 0.60
R² = 0.07
MST recall
PRP contrast β
rSFG, BA9 (44,34,34)
y = -0.04x + 0.83
R² = 0.048
MST recall
PRP contrast β
r precentral sulcus, BA6 (40,6,44)
y = -0.007x + 0.72
R² = 0.0008
MST recall
PRP contrast β
rIFJ, BA9 (42,4,30)
y = -0.02x + 0.76
R² = 0.0098
MST recall
PRP contrast β
lMFG, BA46/10 (-34,44,6)
y = -0.06x + 0.79
R² = 0.03
MST recall
PRP contrast β
lMFG, BA46 (-40,36,32)
y = -0.05x + 0.79
R² = 0.13
MST recall
PRP contrast β


lIFG, BA44 (-52,14,4)
y = 0.007x + 0.70
R² = 0.0006
MST recall
PRP contrast β
lpre-SMA, BA6 (-6,8,52)
y = -0.076x + 0.88
R² = 0.089
MST recall
PRP contrast β
lIFJ, BA9 (-30,6,32)
y = -0.0784x + 0.8261
R² = 0.0408
MST recall
PRP contrast β
lIFG, BA9 (-44,2,34)
y = -0.02x + 0.79
R² = 0.02
MST recall
PRP contrast β
lMFG, BA6 (-28,-4,56)
y = -0.07x + 0.93
R² = 0.07
MST recall
PRP contrast β
lSFS, BA6 (-32,4,46)
y = -0.05 + 0.80
R² = 0.04
MST recall
PRP contrast β

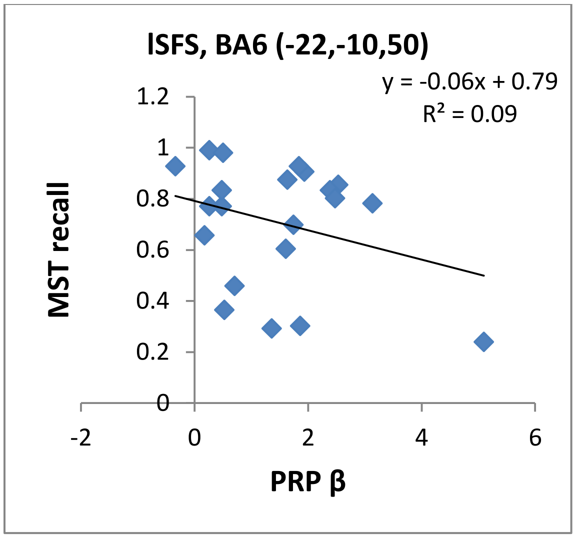
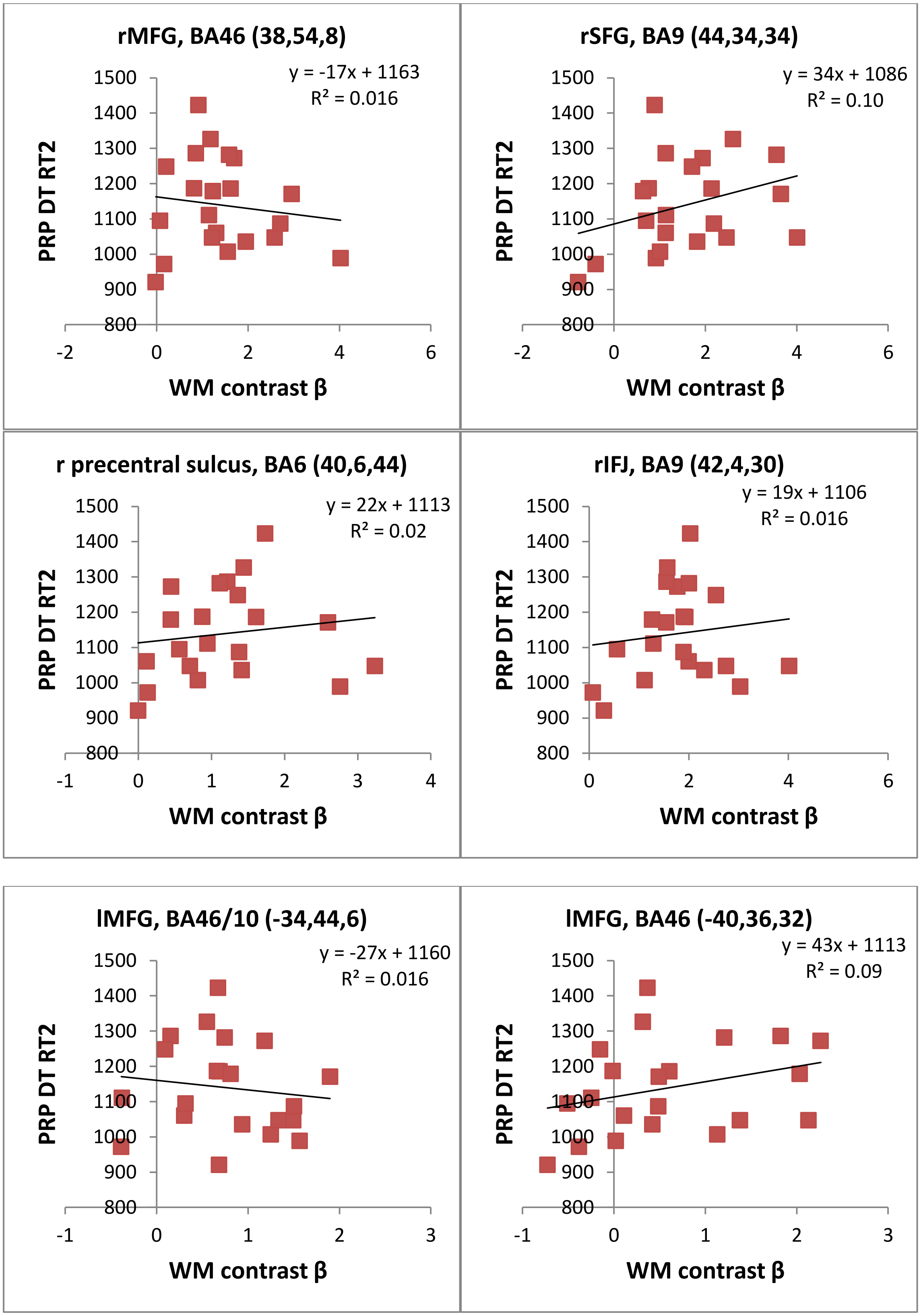


Figure A.0.1: Scatterplot for the other 13 peaks showing the correlation between the brain activity in PRP and the behavioural performance in WM as measured by MST recall.

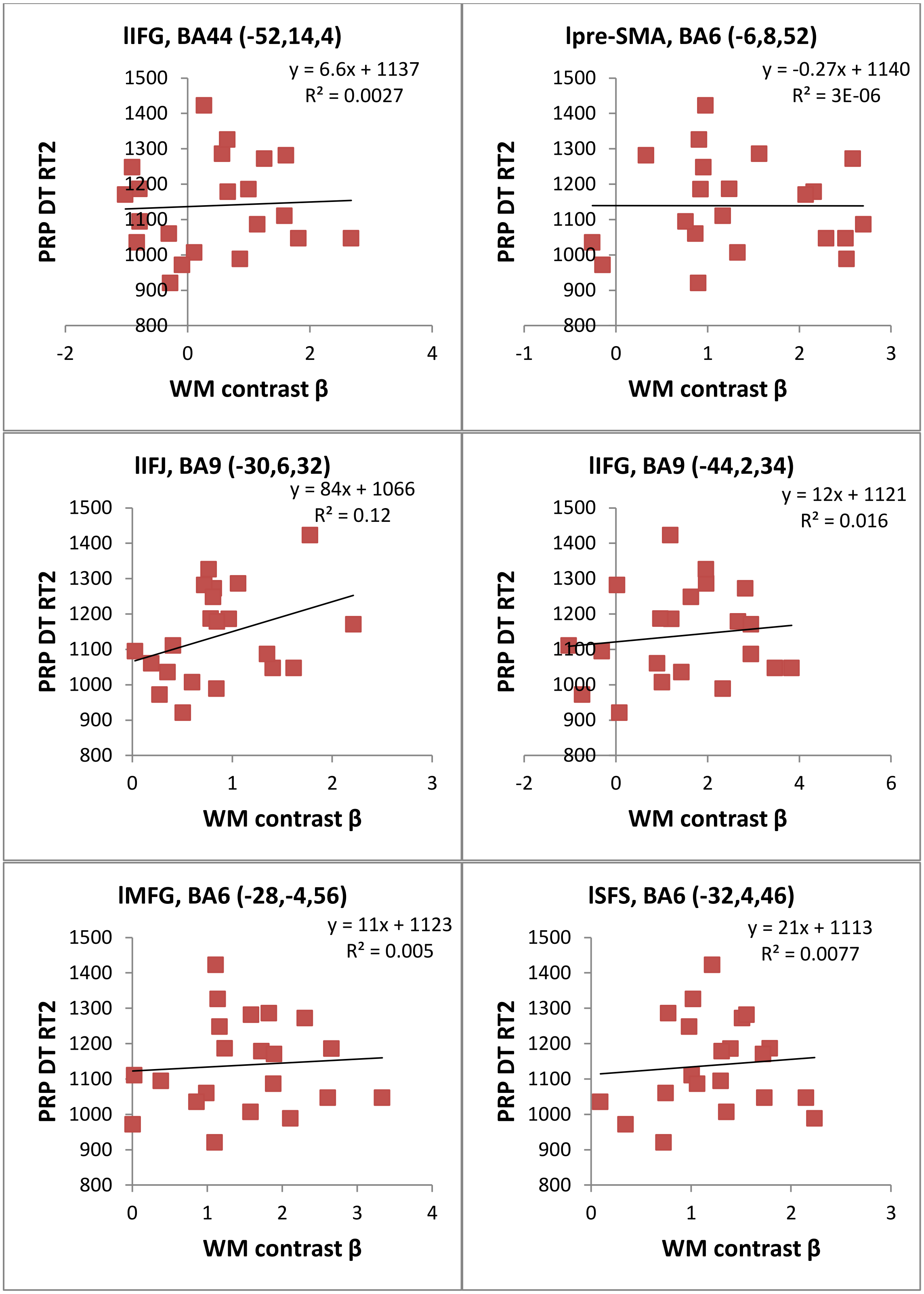
Appendix 7B: Scatterplots showing the correlation between the brain activity in WM and the behavioural performance in DT RT2 for the other 13 peaks

Table A.0.2: Results of Pearson's correlations between the beta values of the WM contrast and DT RT2 of the PRP dual-task for the other 13 peaks.

Peak	r	R^2	p
(38,54,8)	-0.127	0.016	0.292
(44,34,34)	0.318	0.101	0.080
(40,6,44)	0.145	0.021	0.266
(42,4,30)	0.127	0.016	0.292
(-34,44,6)	-0.128	0.016	0.291
(-40,36,32)	0.296	0.088	0.096
(-52,14,4)	0.052	0.0027	0.412
(-6,8,52)	-0.002	0.000004	0.497
(-30,6,32)	0.350	0.1224	0.060
(-44,2,34)	0.127	0.016	0.292
(-28,-4,56)	0.071	0.005	0.380
(-32,-4,46)	-0.088	0.0077	0.353
(-22,-10,50)	0.141	0.020	0.271



rMFG, BA46 (38,54,8)
y = -17x + 1163
R² = 0.016
PRP DT RT2
WM contrast β
rSFG, BA9 (44,34,34)
y = 34x + 1086
R² = 0.10
PRP DT RT2
WM contrast β
r precentral sulcus, BA6 (40,6,44)
y = 22x + 1113
R² = 0.02
PRP DT RT2
WM contrast β
rIFJ, BA9 (42,4,30)
y = 19x + 1106
R² = 0.016
PRP DT RT2
WM contrast β
lMFG, BA46/10 (-34,44,6)
y = -27x + 1160
R² = 0.016
PRP DT RT2
WM contrast β
lMFG, BA46 (-40,36,32)
y = 43x + 1113
R² = 0.09
PRP DT RT2
WM contrast β


lIFG, BA44 (-52,14,4)
y = 6.6x + 1137
R² = 0.0027
PRP DT RT2
WM contrast β
lpre-SMA, BA6 (-6,8,52)
y = -0.27x + 1140
R² = 3E-06
PRP DT RT2
WM contrast β
lIFJ, BA9 (-30,6,32)
y = 84x + 1066
R² = 0.12
PRP DT RT2
WM contrast β
lIFG, BA9 (-44,2,34)
y = 12x + 1121
R² = 0.016
PRP DT RT2
WM contrast β
lMFG, BA6 (-28,-4,56)
y = 11x + 1123
R² = 0.005
PRP DT RT2
WM contrast β
lSFS, BA6 (-32,4,46)
y = 21x + 1113
R² = 0.0077
PRP DT RT2
WM contrast β

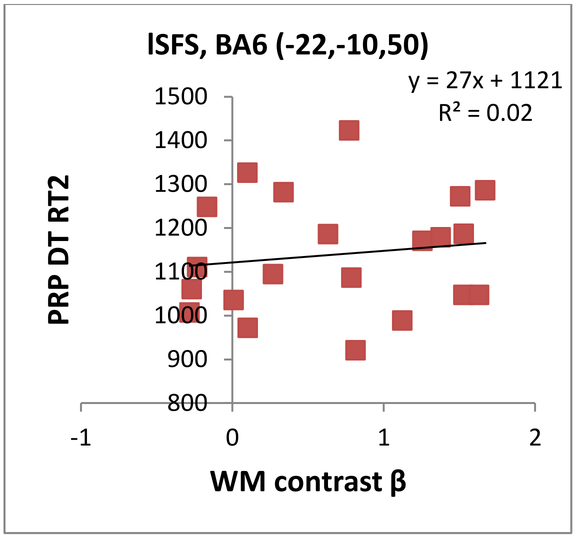
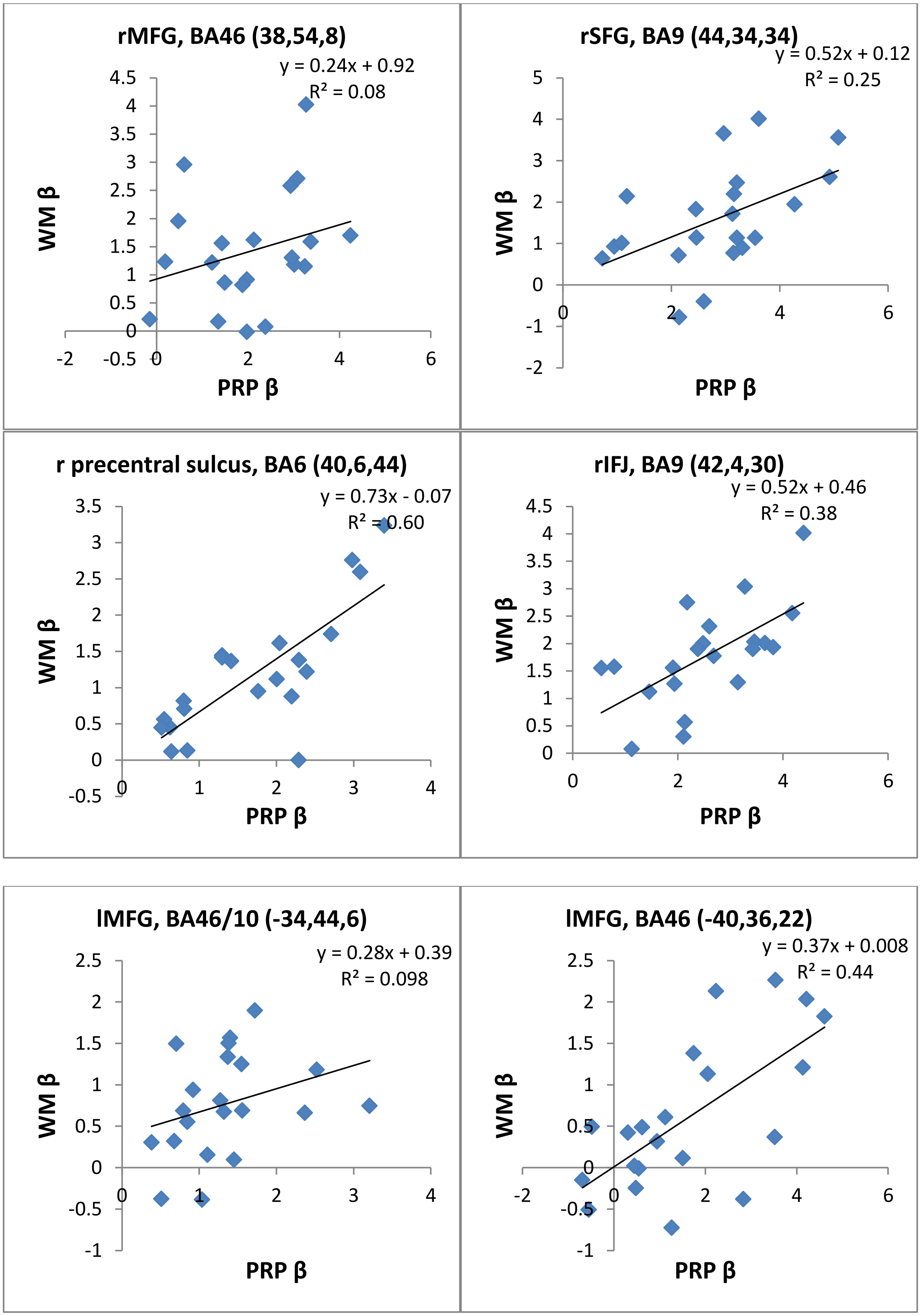


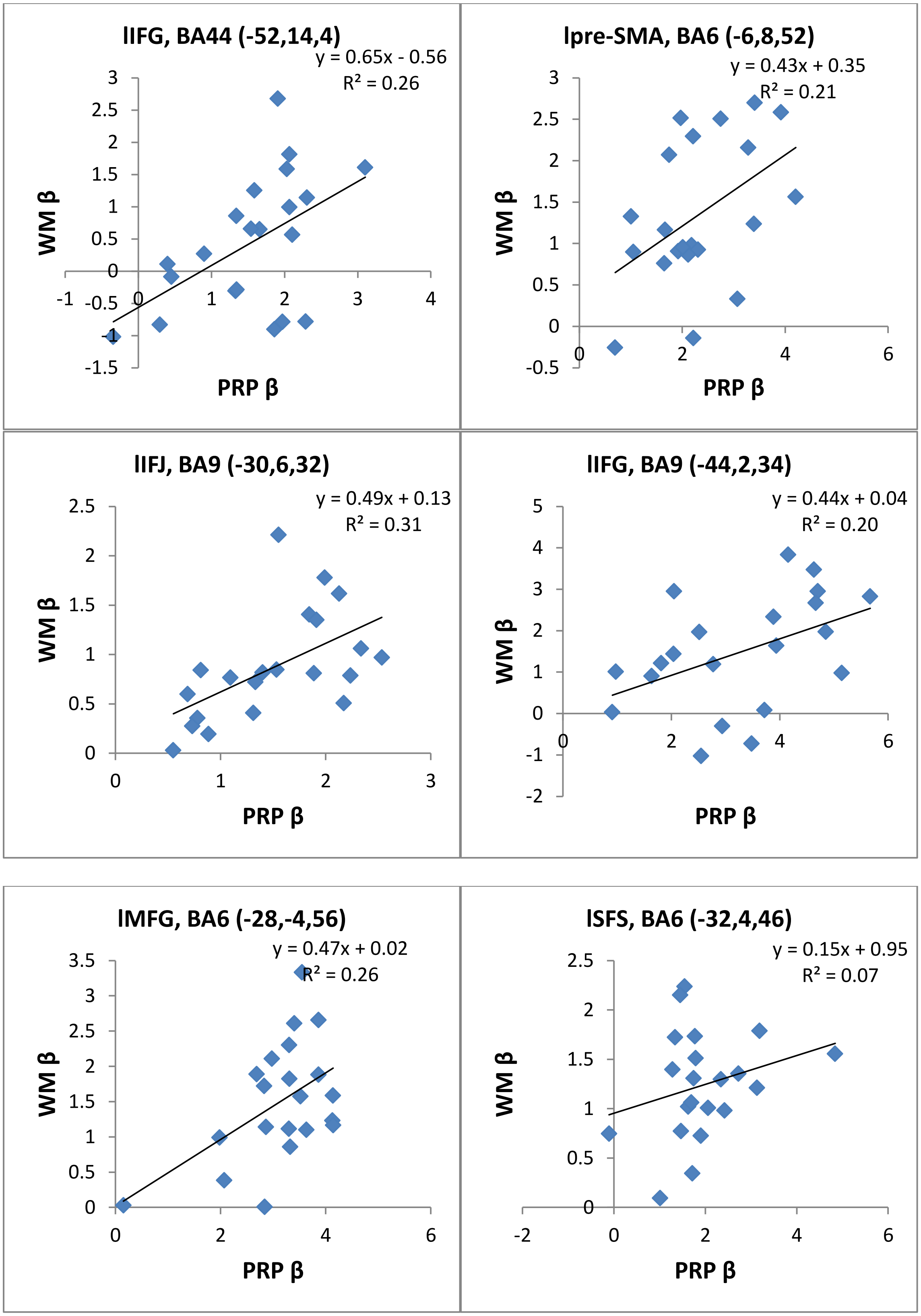
Figure A.0.2: Scatterplot for the other 13 peaks showing the correlation between the brain activity in WM and the behavioural performance in PRP as measured by DT RT2.

Appendix 7C: Scatterplots showing the correlation between the brain activity in PRP and WM for the other 13 peaks

Table A.0.3: Results of Pearson's correlations between the beta values of the PRP and the WM contrast.

Peak	r	R^2	p
(38,54,8)	0.281	0.079	0.109
(44,34,34)	0.504	0.254	0.010
(40,6,44)	0.775	0.601	< 0.001
(42,4,30)	0.620	0.384	0.002
(-34,44,6)	0.312	0.097	0.084
(-40,36,32)	0.661	0.437	< 0.001
(-52,14,4)	0.513	0.263	0.009
(-6,8,52)	0.460	0.212	0.018
(-30,6,32)	0.553	0.306	0.005
(-44,2,34)	0.452	0.204	0.020
(-28,-4,56)	0.509	0.259	0.009
(-32,-4,46)	0.264	0.070	0.124
(-22,-10,50)	0.796	0.634	< 0.001


rMFG, BA46 (38,54,8)
y = 0.24x + 0.92
R² = 0.08
WM β
PRP β
rSFG, BA9 (44,34,34)
y = 0.52x + 0.12
R² = 0.25
WM β
PRP β
r precentral sulcus, BA6 (40,6,44)
y = 0.73x - 0.07
R² = 0.60
WM β
PRP β
rIFJ, BA9 (42,4,30)
y = 0.52x + 0.46
R² = 0.38
WM β
PRP β
lMFG, BA46/10 (-34,44,6)
y = 0.28x + 0.39
R² = 0.098
WM β
PRP β
lMFG, BA46 (-40,36,22)
y = 0.37x + 0.008
R² = 0.44
WM β
PRP β


lIFG, BA44 (-52,14,4)
y = 0.65x - 0.56
R² = 0.26
WM β
PRP β
lpre-SMA, BA6 (-6,8,52)
y = 0.43x + 0.35
R² = 0.21
WM β
PRP β
lIFJ, BA9 (-30,6,32)
y = 0.49x + 0.13
R² = 0.31
WM β
PRP β
lIFG, BA9 (-44,2,34)
y = 0.44x + 0.04
R² = 0.20
WM β
PRP β
lMFG, BA6 (-28,-4,56)
y = 0.47x + 0.02
R² = 0.26
WM β
PRP β
lSFS, BA6 (-32,4,46)
y = 0.15x + 0.95
R² = 0.07
WM β
PRP β

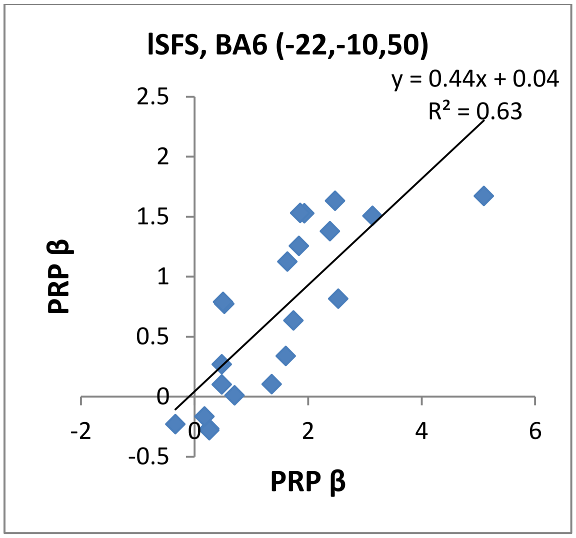


Figure A.0.3: Scatterplot for the other 13 peaks showing the correlation between the brain activity in PRP and WM.

Appendix 8: Documents experiment 5, fMRI study 2

For experiment 5, the ethics form fell under the ethics approval of experiment 4b (Appendix 5A). For experiment 5, the same forms, information sheet (Appendix 1B), consent form (Appendix 1C), demographics form (Appendix 1D), instructions (Appendix 1I), post-questionnaire (Appendix 1J), debrief form (Appendix 1G) and receipts (Appendix 1H) as previous experiments were used. The same MRI forms were used as in experiment 4b, a MRI information sheet (Appendix 5B), a MRI consent form (Appendix 5C), a MRI initial screening form (Appendix 5D) and a MRI second screening form (Appendix 5E).