DOCTORAL THESIS

The Role of Working Memory Load in Distractor Suppression

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The Role of Working Memory Load in Distractor Suppression

by

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Abstract

The well-established Load Theory of Attention and Cognitive Control (Load Theory) has sparked research over two decades. There are two integral components of Load Theory, i.e. ‘cognitive load’ and ‘perceptual load’ with the former concept receiving less attention in the literature. The core assumptions of Load Theory, with an emphasis on ‘cognitive load’, have been systematically investigated in this thesis using electroencephalography (EEG) and transcranial magnetic stimulation (TMS). The current research uncovered robust working memory (WM) effects in the healthy younger adult population which partially supported Load Theory. Experiment 1 revealed that the WM load effect on distractor processing increases when more items were held in WM but can plateau at a certain set-size (i.e., 3 items). In Experiment 2, the direction of distractor interference was inconsistent across the behavioural measures of reaction times and error rates, with the latter in support of Load Theory. In contrast, there was strong electrophysiological evidence (i.e., the N2pc and Pd components) for increased susceptibility to peripheral distractors under low WM load conditions (remembering one item). The behavioural effects of Experiments 1 and 2 which partially supported Load Theory, were not replicated with a TMS protocol (Experiment 3). There were significant effects, partially supporting Load Theory, when the spatial position of distractor and a subsequent target item was considered. Altogether, the findings have contributed to a clearer understanding of WM load effects, especially in terms of the attentional processes involved in distractor processing within a single-task setting. The results have provided recommendations of factors which were omitted in Load Theory such as the distinction of functions (updating and shifting) rather than positing a general executive load. This understanding can inform future research specifically targeting visual processing, WM and selective attention processes which can be extrapolated to everyday situations where attention to detail is crucial.

Contents

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Declaration

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This dissertation has not been submitted, in whole or in part, for any other degree, diploma or qualification at any university.

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Abbreviations

DMTS: Delayed Match-To-Sample

EEG: Electroencephalogram

EF: Executive Function(s)

ERPs: Event-Related Potentials

FC: Fronto-Central

PO: Parieto-Occipital

ROI: Region of Interest

RT: Reaction Time(s)

TEDTOFF: Task-Engagement/Distraction Trade-Off

TMS: Transcranial Magnetic Stimulation

VSTM: Visual Short-Term Memory

WM: Working Memory

WMC: Working Memory Capacity

Chapter 1: General Introduction

Preface

For many years, cognitive psychologists and neuroscientists have been fascinated by the cognitive capacities of humans in the context of attention and working memory (Broadbent; 1958; Baddeley, 2012; Gazzaley & Nobre, 2012; James, 1890; Oberauer, 2019). In the visual environment, an individual must be able to select information (selective attention) and be able to retain and manipulate (working memory) information at the expense of other input. Accumulating evidence suggests that a strong association exists between working memory (WM), attention as observed in overlapping neural structures (Bahmani et al., 2019; Curtis & D'Esposito, 2003; LaBar et al., 1999) and shared capacity limitations (Marois & Ivanoff, 2005). In the review paper by Fougnie (2008), it has been suggested that attention and WM would interact during stages of encoding and manipulation, but attention plays a limited role in the maintenance of information. Despite the overlap in nature of the contents of WM and attention, the precise nature of the relationship between both constructs remains unclear (Fougnie, 2008). WM theorists are more concerned with how information can be maintained temporarily and then accessed and updated efficiently. On the other hand, selective attention researchers have focused on one's ability to successfully encode relevant information (targets) amidst competing irrelevant stimuli (distractors). For example, a selective attention task would require a judgement on one dimension of a stimulus (e.g. colour) while ignoring another (e.g. shape); see section (1.1.1) for more details on selective attention tasks. There have been attempts to incorporate aspects of attention in WM models (Baddeley, 2000; Cowan, 1999; covered in section 1.2) and vice versa (Lavie & Tsal, 1994; see section 1.1 for details). Executive function is also relevant as a "controller" of attention in WM models and as an umbrella term encompassing a range of higher-level cognitive processes in neuroimaging studies, including planning, cognitive flexibility and decision making (Yuan & Raz, 2014). There is evidence for an involvement of the fronto-parietal attention network (Ptak, 2012; Scolari et al., 2015) in which attention is modulated by WM and executive function. Specifically, the dorsolateral prefrontal cortex and posterior parietal cortex which have been frequently implicated in the WM, executive function and selective attention (Katsuki & Constantinidis, 2012). These regions warrant further investigation into their interaction in the context of attentional deployment under conditions of high and low WM load (Wang et al., 2018). One way to investigate attentional capture and WM load is through the modified delayed match-to-sample task combined with a pop-out target stimulus visual search (Fuggetta & Duke, 2017) used in the thesis (see section 1.4 for more detail). The neuroimaging technique (i.e. electroencephalography) was best suited to examine the time course of WM load effects on selective attention (Luck & Kappenman, 2012). Moreover, to uncover the causal role of a specifically targeted brain region, an EEG combined with an online repetitive transcranial magnetic stimulation protocol was employed to modulate the cognitive process of interest (Sandrini et al., 2011; Walsh & Rushworth, 1999). The primary aim of the thesis was to investigate the effects of varying demands in WM on the ability to suppress distracting stimuli and accordingly, test the predictions from Load Theory (Lavie et al., 2004; Lavie & Dalton, 2014). The methodologies that can help address the limitations of the field and the aims of the thesis will be introduced. In this chapter, key definitions and debates surrounding influential models of attention and WM in the visual domain will be outlined including Load Theory (Lavie et al., 2004) due to the limited knowledge of the relationship between both constructs.

The practical application of this programme of research is to act as a bridge between theoretical understanding of visual attention and an individual’s susceptibility towards distractors. For instance, a better understanding of visual attention and distractor interference would improve the shift to online learning platforms as a result of the global COVID-19 pandemic (Salta et al., 2022). A recent study demonstrated the importance of context such as reward in visual search processes which can affect which visual items are prioritised (Le Pelley et al., 2022). Another example of the importance of visual attention in natural settings can be seen in marketing, specifically consumption choices and other factors influencing visual attention (Ladeira et al., 2019). The distractor interference effect examined in this thesis involves intentional suppression of a distractor which mirrors other real-life situations such as searching for a friend in a crowd of people. In terms of everyday visual search tasks where the detection of anomalies is crucial, radiography and airport security (Wolfe, 2020) protocols may benefit from understanding how the visual system and attentional processes work under pressure (with more items held in short-term memory). Whilst the main experimental paradigm examines the shorter timescale of the visual spectrum (Wolfe, 2010), the findings may be eventually extrapolated to other real-life scenarios consisting of visual search within static, foraging or complex scenes.

1.1 Attention

Attention is generally understood as the ability to prioritize relevant stimuli (Desimone & Duncan, 1995; Serences & Kastner, 2014), directed by a person's immediate goal, focusing on one aspect of the environment while ignoring irrelevant aspects (Gazzaley & Nobre, 2012). Selective attention has been defined as the ability to focus and avoid interference from distracting information (Bundesen, 1990; Johnston & Dark, 1986; Treisman, 1969). Most psychological experiments create competition for limited attentional resources between distractor and target stimuli thus inducing a *selection filter*, in which features of some stimuli processed to a greater extent than those of other stimuli. Early selection theories (e.g. Broadbent, 1958) initially postulated that attention filters sensory input based on low-level physical features such as the orientation or colour of a line. An example of an automatic bias in attentional selection is 'priming of pop-out' (Maljkovic & Nakayama, 1994). A standard priming study requires observers to search for a target defined by its unique feature amongst distractors, for instance, a green target among red distractors or vice versa. There is facilitation of performance such that quicker response times are observed for features which have been presented in previous trials (i.e. recent experience). This automatic bias also extends to features such as spatial position of previous target (Maljkovic & Nakayama, 1996) and difficult visual search tasks where the target is hard to find (Wang et al., 2005). However, Treisman's attenuation account (1960) stated that the unattended stimulus was not completely eliminated from the processing stream, but had simply not reached the threshold for conscious awareness. Late selection theories (e.g. Deutsch & Deutsch, 1963) posited that the filtering process takes place after both unattended and attended stimuli are processed to the level of semantic analysis. Evidence for the attenuation process comes from studies in which participants were able to recall information from the unattended ear in speech shadowing (i.e.

repeating speech immediately after hearing it) tasks that were of personal relevance (Conway et al., 2001) or emotionally salient (Nielsen & Sarason, 1981).

1.1.1 Load Theory

The burgeoning interest in resolving the early versus late selection debate sparked the development of an influential theory of attention known as the Perceptual Load Theory (Lavie, 1995; Lavie & Tsal, 1994) and eventually the Load Theory of Selective Attention and Cognitive Control (“Load Theory”: Lavie et al., 2004). The idea that perception is capacity-limited has not been refuted within the Load Theory framework (Lavie & Dalton, 2014). Lavie (1995) adopted an intermediate stance in that perceptual load, which taxes perceptual capacity (via the number of items or processing requirements of a task) could account for the filtering process which leads to either early or late selection. In contrast, *cognitive load* where demands are placed on executive control functioning such as remembering more items in WM reduces the ability for an individual to exert attentional control (De Fockert, 2013; Lavie, 2005). Two different mechanisms have been distinguished within Load Theory; a *passive* perceptual selection mechanism and an *active* attentional control mechanism (Lavie et al., 2004). The passive mechanism allows for the exclusion of irrelevant distractors under conditions of high perceptual load (Lavie, 2005). Distractor interference is reduced under this condition as there is insufficient capacity for distractors to be perceived. The active mechanism works by excluding irrelevant distractors which have been perceived such that current processing priorities can be maintained. High load on cognitive functions such as WM, leads to increased distractor processing as there is less capacity available for active control (Lavie & Dalton, 2014). Low perceptual load effects are consistent with late selection views in that all information such as targets and distractors are processed which necessitates late selection (Rees et al., 1997). When perceptual load is high, there is insufficient capacity to process distracting information which is consistent with early selection (Lavie & Cox, 1997). Successful selective attention would only be achieved if the demands of the relevant task were sufficient to exhaust perceptual capacity such that there is no spillover of perceptual processing to irrelevant information (Lavie & De Fockert, 2006). For instance, Rees and colleagues (1997) found that distracting visual motion was not processed under high perceptual load compared to the low perceptual load condition. This applies to externally generated stimuli as well as internally generated information such as 'mind wandering' (Forster & Lavie, 2009). The studies in support of perceptual load effects have originated mainly from Lavie's lab (Forster & Lavie, 2008a; 2008b; Lavie & Cox, 1997; Lavie & De Fockert, 2003) and partially replicated by others (Ahmed & De Fockert, 2012b; He & Chen, 2010; Wei et al., 2013).

The predictions for cognitive load, the active attentional control mechanism which relies on higher cognitive functions such as WM, were the opposite of perceptual load. Under high cognitive load, there was reduced capacity in WM for active control leading to the processing of distractors. More specifically, there was reduced capacity to distinguish between relevant and irrelevant targets and an impaired ability to prioritize relevant stimuli. Top-down settings such as task instructions are necessary for relevant information to be given higher priority while suppressing irrelevant information (Lavie, 2010). As an extension of Load Theory, Konstantinou and Lavie (2013) distinguished between different types of WM load in visual detection, i.e., visual maintenance and cognitive control functions of WM. The authors postulated that the ability to ignore distractors was influenced by the type of processing load involved in the current task. When visual maintenance functions were loaded, there was an increase in demand for the sensory processing capacity in visual perception akin to what is involved in perceptual load. In high cognitive control load conditions, there was reduced availability to prioritize task demands, thus distractors were processed to a greater extent. The extension of terminology by Konstantinou and

Lavie (2013) beyond perceptual load was an attempt to account for contradictory results such as those found in a Navon task (e.g., Ahmed & De Fockert, 2012b). Ahmed and De Fockert (2012b) demonstrated increased distractor interference for hierarchical stimuli but not when the distractor was processed at a local level. A hierarchical stimulus refers to a large global shape made up of smaller local shapes, for instance, a "H" shape made up of smaller "S" letters. Given that perceptual load and cognitive load exerted opposite effects, it was important for studies to precisely determine which mental processes are loaded by a task (Lavie et al., 2004). The opposite effects of load (increased distraction with high cognitive control load but less with more perceptual load) argue against the idea that task difficulty could account for the effects of either type of load (Lavie, 2010). There have been implications for Load Theory in that refinements should be made and not necessarily discrediting the framework. Zhang and Luck (2015) have attempted to frame perceptual load as "resolution load" whereas WM load was termed "capacity load" because they have distinguished the different processes involved in attention. Resolution load refers to the fine-grained discrimination of stimuli whereas capacity load refers to concurrent processing of multiple stimuli (Li et al., 2019; Zhang & Luck, 2015). There are suggestions made by researchers outside of Lavie's research group (e.g., Burnham et al., 2014; Lin & Yeh, 2014; Park et al., 2007).

Load Theory has been challenged over the years by rival theories such as the visual dilution account (Benoni & Tsal, 2010; Tsal & Benoni, 2010) as an explanation for discrepancies in perceptual load effects. The dilution account differs from Load Theory in that there is no differentiation between relevant and irrelevant for additional items. According to the dilution hypothesis, only one item is relevant within the focused attention stage while all other items become irrelevant. It is predicted that the dilution effect (i.e., less differentiation between relevance of additional items) increases as a function of set-size and results in decreased distractor interference (Chen & Cave, 2013; Wilson et al., 2011). Additionally, Specialized Load theory has highlighted the importance of distinguishing between different types of cognitive load (Park et al., 2007). The effect of cognitive load on selective attention could differ depending on the degree of overlap between the concurrent load with targets or distractors (Kim et al., 2005). Other theories have emphasized various factors which can modulate selective attention such as individual differences in WMC ("the Task-Engagement/Distraction Trade-Off theory - TEDTOFF": Sörqvist & Rönnberg, 2014), trait anxiety ("Attentional Control Theory": Eysenck et al., 2007) and different attentional networks (Fan et al., 2002).

Three main experimental paradigms have been used to measure selective attention in relation to Load Theory. Firstly, the Eriksen Flanker task was initially created as a measure of inhibitory control, which is also considered an executive function (Eriksen & Eriksen, 1974). In this paradigm (Figure 1.1), participants would respond to a target stimulus according to the current goal by overriding dominant responses. For example, the target arrow (">") would be 'flanked' by congruent (same direction of arrow), incongruent (opposite direction of arrow: "<") or neutral (no arrow) distractors. It has since been adapted using different stimuli than arrows and spatial positions beyond left and right (Posner & Peterson, 1990). The Flanker task is versatile because both perceptual and WM load could be manipulated in several ways, for example, manipulating perceptual load by alternating the number of items on display (Lavie & De Fockert, 2003). In Lavie and De Fockert's (2013) experiment, participants had to identify which of the target letters "X" or "N" were on display whilst ignoring peripheral distractor letters. Distractor interference was calculated by subtracting response times to targets from trials containing congruent versus incongruent distractors (incongruent minus congruent). Furthermore, the similarity of target and non-target items could be manipulated by angularity (Figure 1.2), with the letters "K" and "V" being more similar to the target than the letter "O" (Beck & Lavie, 2005). Additionally, it was expected that distractors placed within foveal regions, at fixation, were better represented and would induce faster response times than distractors at peripheral locations (Beck & Lavie, 2005).

Figure 1.1

Example of Stimuli Used in an Eriksen Flanker Task (Eriksen & Eriksen, 1974). The Target Arrow is the Arrow Placed at the Centre of the Screen.

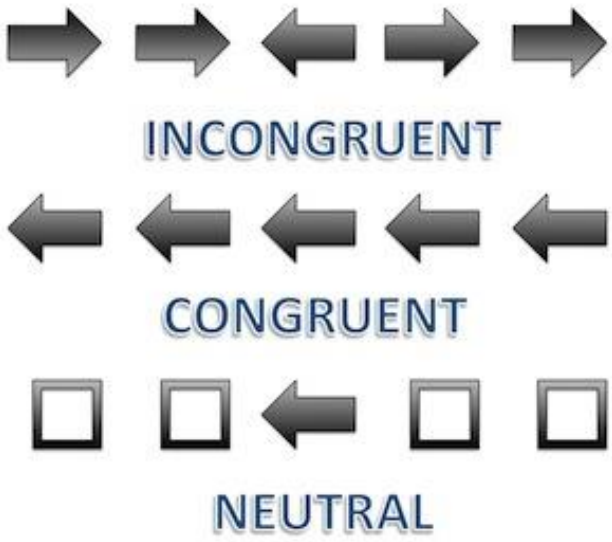
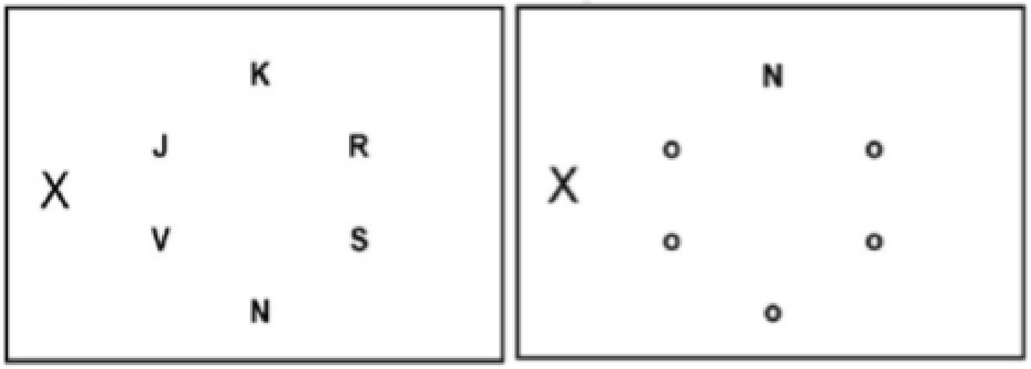


Figure 1.2

Example of Visual Array from a Search Task (Beck & Lavie, 2005). The Experimental Conditions from Left to Right Represent High (Amongst Other Letters) and Low (Amongst Other Placeholders) Perceptual Load Respectively. “X” in the Periphery is a Distractor While “N” is the Target Item.



Secondly, the Stroop task (Stroop, 1935) has been characterized by the delay in response times between congruent and incongruent stimuli. In this particular task, a mismatch between the name of a colour and the colour that it is presented in (e.g., “RED” printed in blue ink) resulted in slower response times and more errors. Earlier studies using the Stroop task required a verbal response from participants whereas more contemporary studies require button pressing (Flaudias & Llorca, 2014; Macleod, 1991). Thirdly, inattentional blindness (IB) occurs when an individual fails to notice an unexpected stimulus due to a lack of attention or awareness rather than deficits in vision (Mack & Rock, 1992). A well-known example would be that a salient and dynamic stimulus (gorilla) went unnoticed as attention was diverted towards another visual task (Simons & Chabris, 1999). Fougnie and Marois (2007) found that IB to unexpected stimuli occurred to a lesser extent when participants were completing a more demanding cognitive task, which was deemed as increased task difficulty (Konstantinou & Lavie, 2013). Their findings lend support to perceptual load effects in that the manipulation-of-information condition reduced distractor interference more than the task requiring simple maintenance of information. Moreover, Cartwright-Finch and Lavie (2007) contributed empirical support for this effect, high perceptual load significantly reducing the awareness of task-irrelevant stimuli.

The lack of specificity when defining cognitive load may have contributed to the inconsistent replications of cognitive load effects (Murphy et al., 2016). In studies investigating cognitive load effects, participants would complete a ‘sandwich task’ (De Fockert et al., 2001). Participants would be presented with information to remember and maintain, which would be probed at a later point within the trial. During the retention interval, they would be asked to perform a response-competition visual search task (mainly Flanker, Stroop or IB task). The majority of studies has manipulated visual and auditory attention (Rissman et al., 2009) but there has also been research interest in tactile selective attention (Dalton et al., 2009). In Rissman and colleagues’ (2009) study, they found greater neural activity (i.e., fMRI activation) under high WM load when participants were told to ignore visual scenes and faces. When the visual scenes were made relevant to the task, they found no effects of WM load on neural activation. Findings from their study suggested that WM load effects were specific to distractor processing, although the term *task relevance* has been criticized by other authors (Lleras et al., 2013). It is worth noting how WM load has been quantified across several studies, as it has been established that WM is not a unitary construct. Generally, the interleaved WM load has been operationalized using verbal material, despite the overarching research focus on visual attention: there has been verbal rehearsal load (Konstantinou & Lavie, 2013; Konstantinou et al., 2014), the memory retrieval of digits in sequential or random order (Lavie et al., 2004; Lavie & De Fockert, 2005) and probing letters from previous trials, i.e., n-back method (Scharinger et al., 2015).

1.1.2 Defining Distraction and Distractors

According to Lleras and colleagues (2013), it is important to differentiate between the concept of “distraction” and “distractor interference. This group of researchers found the conception of distraction critical in selective attention studies. They have proposed terms such as ‘candidates’ and ‘foils’ to more appropriately label distractors. Candidates refer to a subset of items that contains at least some of the important attributes of a target such as spatial position or visual similarity. Candidates can only be determined once a task has been defined and the target of the attention system is known. In visual search tasks, the number of candidates determines the functional set-size for a scene. Candidates are considered as potential ‘targets’ thus making them relevant to the task but do not have a stimulus-response association. On the other hand, a foil is a type of candidate that can interfere with a participant’s task performance by closely matching the defining attribute as the set of targets (similar to Bundesen, 1990). The term foil should be used in reference to congruent and incongruent distractors. The most important of these criticisms is that the conclusions drawn from Flanker tasks (Eriksen & Eriksen, 1974) and the Stroop effect (Stroop, 1935) do not measure distractibility in the same way that IB tasks do (Lleras et al., 2013). In a Flanker task, attention is utilised to select and scrutinise foils in order to execute response inhibition of non-target stimuli. This is in support of attention working as an early filter driven by an individual’s goals. This is in contrast to irrelevant and unexpected stimuli used in IB studies. Lleras and colleagues (2013) argue that a distractor which is task-relevant will not tell anything about distractibility. However, the Flanker effect seems to indicate the efficiency of the visual system in simultaneously performing the task whilst processing other candidates from the display. Nonetheless, the keyword “task-irrelevant distractors” remains prevalent and misused in a majority of psychological studies. It is important to consider the explanatory power of findings derived from the types of distractors used in visual search paradigms. It is important to consider the nature of distractors and their relationship to the attended target when interpreting attentional modulations. Therefore, the findings from this thesis inform our understanding of distractor interference i.e., within-task effects rather than distraction which is the preoccupation of the mind by thoughts or stimuli that a person had no a priori intentions to be processed.

1.2 Working Memory

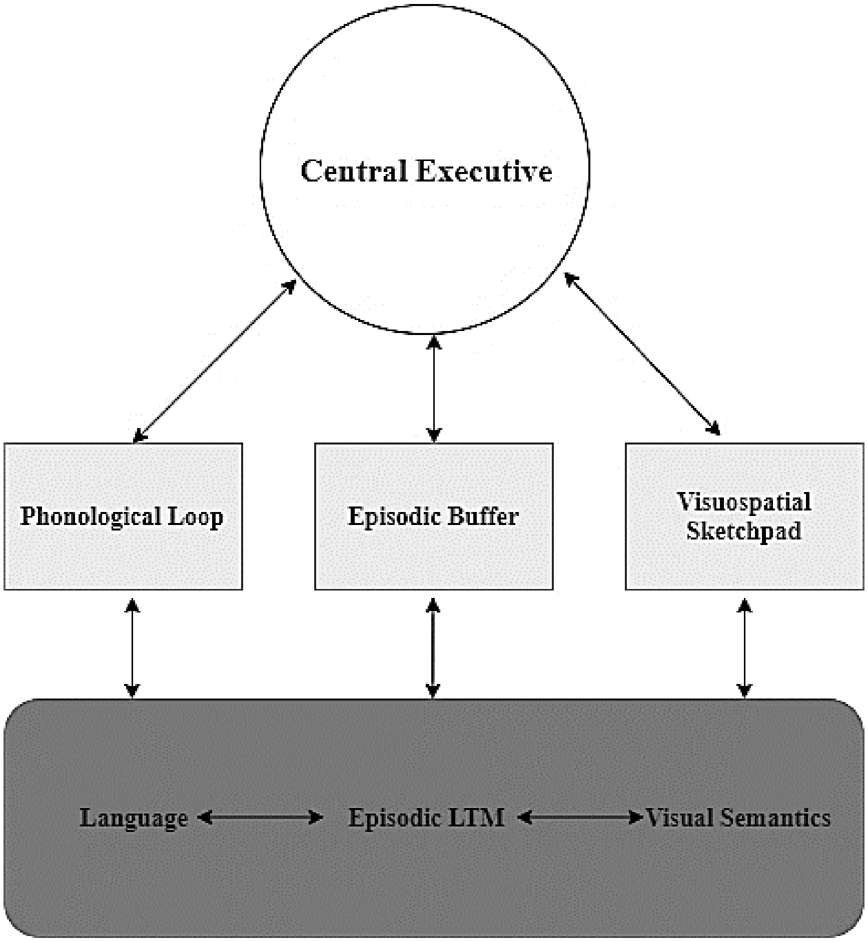
The existence of two separate memory stores, short-term (STM) and long-term (LTM) memory, has become a core principle in cognitive psychology based upon an earlier assumption of primary and secondary memory respectively by James (1890). The terms WM and STM have been used interchangeably by researchers in an inconsistent manner (Norris, 2017). However, WM differs from STM in that the latter is a single component i.e., “passive” store whereas the former entails multiple components according to Baddeley & Hitch (1974). As for Cowan (2008), WM encompasses STM whereas Engle (2002) has applied the term WM specifically to attention-related aspects of STM. The term WM was first conceived by Miller and colleagues (1960). The idea of the mind working analogous to a computer, was then adopted by Atkinson and Shriffin (1968) in the context of short-term storage. Investigations into WM has expanded across multiple domains such as selective attention (De Fockert et al., 2001), brain injury (Perlstein et al., 2004) and ageing (Rhodes et al., 2016). Although there are several models of WM (see section 1.2.1), there is a consensus that WM is of limited capacity and allows for the brief storage and manipulation of information associated with the current task or goal (Baddeley, 2007). Views within different theories of WM can be arranged on a continuum from domain-specific to domain-general, in favour of automaticity of attentional processes or not and the model’s focus on either group norms or individual differences (Adams et al., 2018). For example, the Embedded Processes Model (Cowan, 1999) emphasizes the role of WM maintenance by activating long-term memory (LTM) traces without the need for separate buffers according to the type of stimulus. Engle and Kane (2004) stressed the importance of individual differences in WM capacity (WMC). The primary WM model discussed in the thesis is the Multi-Component Model (Baddeley, 2012; Baddeley & Hitch, 1974) and secondary WM model being the Embedded Processes Model (Cowan, 2001), because they are fundamental to executive function (Diamond, 2013) and selective attention (Gazzaley & Nobre, 2012).

1.2.1 Multi-Component Model of Working Memory

The multi-component model of WM by Baddeley and Hitch (1974) has become a widely used and enduring theoretical framework over time (Baddeley, 1996; Hasher & Zacks, 1988; Lavie et al., 2004; Logie et al., 2020; Miyake & Shah, 1999), because the model has been supported in many situations. The model surpassed limitations and issues of unitary systems faced by an earlier model known as "the modal model" (Atkinson & Shiffrin, 1968). For example, individuals were able to remember equally well in two tasks which engaged different domains of information such as auditory and visual versus a single-task condition where they would remember information from a single modality. This pattern of findings can be accommodated by Baddeley and Hitch's (1974) proposal of three specialized stores known as the phonological loop (PL), visuo-spatial sketchpad (VSS) and the central executive (Figure 1.1). The PL and VSS are considered to be passive storage systems. The PL has been shown to consist of a fast-fading phonological store and an articulatory process that prevents memory traces from decaying and thus being forgotten (Repovs & Baddeley, 2006). The VSS has been fractionated into discrete stores for spatial and visual information (Klauer & Zhao, 2004). Logie and Pearson (1997) proposed a distinction between a passive visual storage component ("visual cache") and a dynamic spatial retrieval component ("inner scribe) although the nature of visuo-spatial rehearsal remains unclear (Baddeley, 2012). The central executive (CE) was hypothesized to act as a control system of information to its subsystems which function as storage for verbal and visuospatial content independently. The CE is linked with executive functions and high-level cognition such as the guidance of attention, planning and decision making (Baddeley, 1998). Due to the model's linearity, the episodic buffer component (Baddeley, 2000) was added later without a drastic transformation of the overall model. According to the theory, the episodic buffer represents a multimodal interface and can be accessed by the CE via conscious awareness. The episodic buffer serves to feed information into and retrieve information from episodic long-term memory, similar to Tulving’s (1989) concept of episodic memory. Although the Baddeley model is ideal for examining effects of modality, some researchers have criticized Baddeley’s model for basing assumptions on the effects observed within his own laboratory (Adams et al., 2018).

Figure 1.3

The Multicomponent Model of Working Memory Adapted from Baddeley (2003)

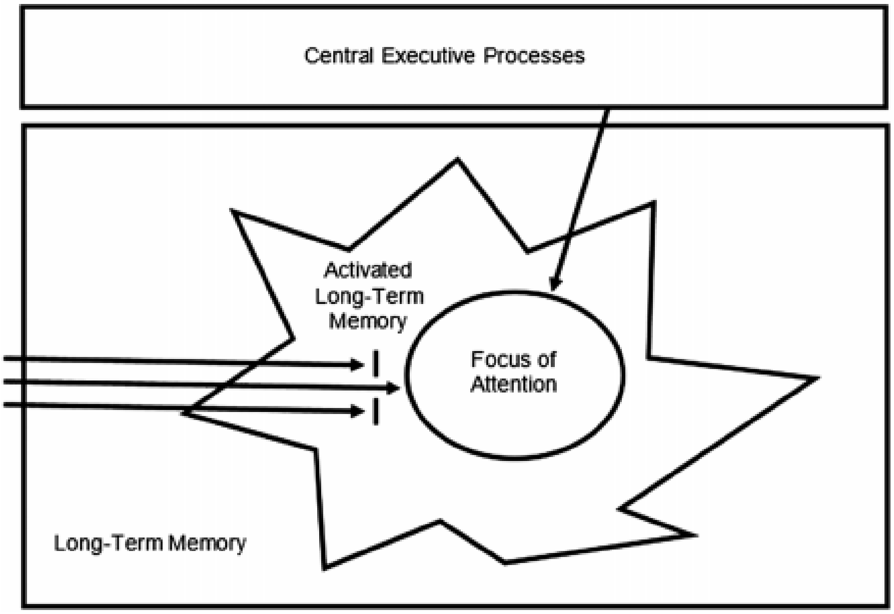


Note. The dark grey areas represent long-term "crystallised" systems. The light grey areas represent "fluid" systems. The episodic buffer is the interface between long-term memory and sub-systems of WM.

In contrast, the Embedded Processes Model of WM (Cowan, 1999) is regarded as a more general framework of information processing. There are several components such as a central executive, long-term memory, active memory and the focus of attention (Figure 1.2). This model has challenged the view that there are multiple discrete systems within short-term storage and posits that the information is stored at varying levels of activation. Cowan (1999) and Oberauer (2009) proposed the idea that attention controls the activation of existing long-term memory representations and information from the external environment as an embedded subset of information in WM. Cowan’s model of WM is not necessarily incompatible with Baddeley’s model, as the activated elements in memory roughly correspond to passive stores like the phonological loop (Mizuno, 2005). Only one representation is considered explicitly for current processing and this short-term store (i.e., “focus of attention”) is not specific to any modality. However, this store is still susceptible to interference from previously activated information or new input overwriting it. The central “controller” can counteract interference or overwriting via attentional refreshing to prevent the activation from decaying over time especially earlier items which are more likely to have been deactivated or displaced from the focus (Lewandowsky & Oberauer, 2008). The information that is actively recalled is subject to this capacity restriction and only the information within the focus can be accessed via conscious awareness (Cowan, 2001).

Figure 1.4

The Embedded Processes Model Retrieved from Adams et al., (2018)



1.2.2 Working Memory Capacity and Attention

The conceptualization of WMC differs between researchers who are interested in short-term memory storage versus researchers who are interested in how information in WM is manipulated (reviewed by Wilhelm et al., 2013). WMC has been viewed as executive attention (Engle, 2002; but see Oberauer, 2019 regarding the ambiguity of this term), as primary/secondary memory (Unsworth & Engle, 2007) or as the ability to form rapid binding of items (Oberauer, 2009). According to Engle’s (2002) definition of WMC, WMC reflects variation in the ability to control attention for active maintenance of information rather than the number of items in immediate storage. WMC can be measured through a complex span task requires a person to remember items, whilst being interrupted by another processing task (Redick et al., 2012). For example, an operation span task entails interleaved mathematical equations with to-be-remembered letters. After 3 to 7 equation-letter pairs, the participant must recall the letters according to the sequential order of presentation. It has been found that participants who exhibited superior performance on complex span tasks also performed better in measures of attentional control and enhanced memory retrieval compared to the lower scoring group (Shipstead et al., 2014; 2015; Unsworth et al., 2004). WMC has been associated with higher-level cognition such as intelligence (Kane et al., 2005), reasoning (Barrouillet & Lecas, 1999) and EF (McCabe et al., 2010). WMC has been conceptualised as a unitary executive attention construct closely linked to the CE component of WM which entails the coordination of multiple cognitive functions (Salthouse, 1990; Unsworth & Engle, 2007). The role of WMC has been demonstrated in situations where controlled attention is necessary such as processing target-related information amidst interference or distraction (Fukuda & Vogel, 2009; Kane & Engle, 2004). Extensive research has shown that WM and attention are inherently linked (Chun, 2011; Gazzaley & Nobre, 2012, Kiyonaga & Egner, 2014; reviewed by Chai et al. 2018). In a recent review, the conceptualization of attention has been described as either a resource that is responsible for limited capacity of WM or as a selection mechanism in how different forms of attention interact with WM (Oberauer, 2019).

Although the majority of Load Theory studies reference Baddeley's model (2003; 2010), the inclusion of key concept such as Cowan's K has been integrated in several discussions linking WMC and attention. "Cowan's K" (Cowan, 2001), an estimate measurement of visual WM has been applied (e.g., Konstantinou & Lavie, 2013; Konstantinou et al., 2014; Roper & Vecera, 2014). It is calculated as (hit rate + correct rejection rate – 1) multiplied by N, indicative of the number of items to be remembered (Cowan et al., 2005). Cowan (2001) has found that WM is limited in capacity averaging around 4 ± 1 representational units as opposed to the traditional finding of 7 ± 2 items (Miller, 1956). Cowan's capacity estimations seem to uphold across a wide variety of stimuli such as shaded cubes, coloured squares, Chinese characters and random polygons (Alvarez & Cavanagh, 2004). For instance, it has been shown that WMC has a limit of 3-4 items for simple visual stimuli such as oriented bars (Cowan, 2001; Luck & Vogel, 1997). The difference in Cowan's K capacity reflects the difference in capacity between conditions within participants rather than an absolute estimate of capacity limits for a discrete number of items (Cowan, 2001). By using the individual-differences approach, dominant theories of attention (see section 1.1.1) such as Load Theory (Lavie et al., 2004) and the TEDTOFF theory (Sörqvist & Rönnberg, 2014) have associated Cowan's K with the susceptibility of processing distractors. The theoretical assumption within Load Theory (Konstantinou & Lavie, 2013; Konstantinou et al., 2014) in relation to WMC, is that the level of processing distractors relies on the extent to which WMC resources are engaged. The prediction here would be that individuals with lower WMC are more likely to process distractors (e.g., Vogel et al., 2005). In contrast, the TEDTOFF theory (Halin et al., 2014; Sörqvist & Marsh, 2015) was based on studies where an increase in task difficulty helped to reduce the adverse effects of background auditory noise. Additionally, the TEDTOFF theory would predict that individuals high in WMC would perform better due to being more able to resist the attentional capture from background sound (Sörqvist et al., 2013; Sörqvist & Rönnberg, 2014).

The biggest challenge faced by WM storage theorists is whether this observed capacity is a result of continuous resources (Bays & Husain, 2008; Ma et al., 2014) or is bound by finite slots (Adam et al., 2017; Awh et al., 2007; Vogel & Machizawa, 2004). A way of differentiating the slot model from the resource model is that the former adopts an all-or-nothing approach in that excess items are not remembered whereas the resources model assumes that WM resources can be distributed amongst all items but with lower resolution (Ma et al., 2014). The stance regarding the *fixed slots* versus *continuous resources* debate (Zhang & Luck, 2008) should be noted as neutral as the scope of the thesis was not to test either theory directly.

1.3 Executive Function

The concept of Executive Function (EF), synonymous to "cognitive control", was termed as a "Central Executive" in Baddeley and Hitch's (1974) model of WM, which suggests that these psychological constructs are intrinsically linked. In line with the development that WM is not a unitary system, studies have demonstrated that EF comprises of several components and the number of subcomponents fluctuates depending on the model (Jurado & Rosselli, 2007). Table 1 provides a short list of how EF has been defined over time, which highlights the lack of clarity in defining the term. However, there is a general consensus that EF allows the flexible shifting of an individual's mindset to adapt to changes in the environment whilst inhibiting behaviours which are not consistent with a current goal. Generally, higher level cognition such as planning is considered as an EF. According to Diamond (2013), research into EF is important, as these functions are relevant to aspects of everyday life, including quality of life (Davis et al., 2010) and job success (Bailey, 2007). Impairments in EF play a role in explaining mental health disorders such as attention deficit disorder (Diamond, 2005) and schizophrenia (Barch, 2005) as well as the tendency to procrastinate in a sample of university students (Rabin et al., 2010).

Table 1a

List of EF Components and Their Definitions Adapted from Jurado & Rosselli (2007)

Author	Components of Executive Function
Baddeley & Hitch (1974)	Central executive, phonological loop, visuospatial sketchpad
Lezak (1983)	Volition, planning, purposive action, effective performance
Norman & Shallice (1986)	Supervisory attentional system
Delis et al. (2004)	Flexibility of thinking, inhibition, problem-solving, planning, impulse control, concept formation, abstract thinking, creativity
Banich (2009)	Purposeful and coordinated organization of behavior. Reflection and analysis of the success of the strategies employed.

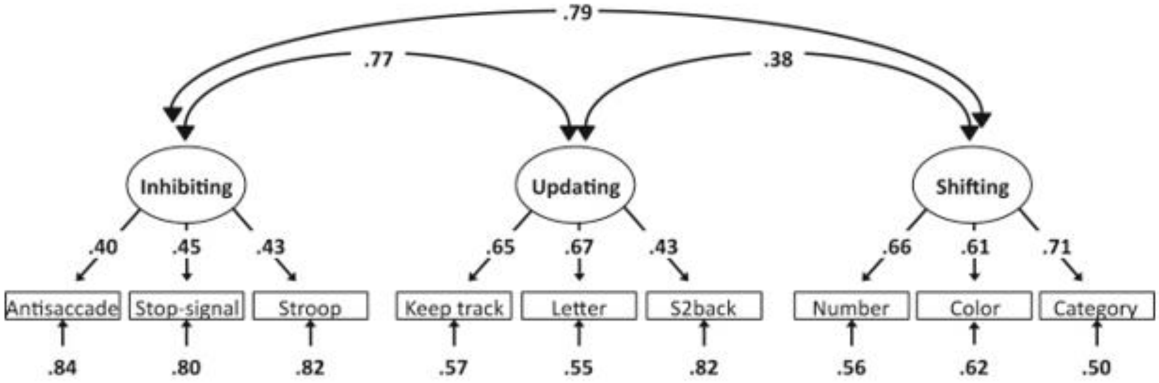
Traditionally, EF or "executive processes" have been synonymously referred to as frontal lobe functions when investigating cognitive functions related with the voluntary control of behaviour (Knight & Stuss, 2002), and a majority of studies with prefrontal lobe lesion patients have reported disruption to normal performance on EF tasks (Alvarez & Emory, 2006; Luria et al., 1966). EF tasks have been designed to recruit the frontal lobe regions but are not specific to those areas. For instance, patients with non-frontal brain lesions performed equally poorly to frontal lobe lesion patients (Anderson et al., 1991; Robinson et al., 1980). Results from lesion studies should be taken with caution as lesion damages are idiosyncratic and are hard to experimentally control for across participants (Adolphs, 2016). The inherent complexity of executive functioning most likely entails the coordination between frontal and non-frontal regions (Alvarez & Emory, 2006). Therefore, one issue faced by researchers investigating EF is the issue of task impurity in that most EF tasks are likely to measure multiple functions (reviewed by McCabe et al., 2010). Stuss (2011) has disputed the idea that the frontal lobes equal a central executive but rather EFs signify only one functional category within the frontal lobes. As previously described, EFs have been identified to be non-unitary in nature (Jurado & Rosselli, 2007). Stuss and Levine (2002) posit that the variability in findings may be due to the complexity of EF tasks, which recruit an increasing amount of mental resources in frontal regions alongside progressing levels of complexity.

1.3.1 The Unity and Diversity Model of Executive Function

One approach was to view EF as a “macroconstruct” in which several subprocesses of EF work in unison to resolve higher level cognition such as problem-solving and making complex decisions (Zelazo et al., 1997). Executive control encompasses high-level cognitive functions which organise and regulate goal-directed behaviour such as planning, interference control, working memory, task-switching, and task coordination (Miyake et al., 2000). Miyake and colleagues’ (2000) dominant model of EF has identified at least three separate yet overlapping EFs; shifting, updating, and inhibition governing attentional control (Figure 1.3). *Shifting* involved the flexible switching of attention between tasks or mental sets. This function involves using attentional control to enhance task performance. The *Updating* function generally refers to the continuous monitoring and replacement of information in WM. Morris and Jones (1990) posited that updating involves a dynamic modification process of out-dated information influenced by new input. Other researchers viewed the updating function as a transient short-term storage of information rather than attentional control per se (Eysenck et al. 2007). The *Inhibition* function involves using attentional control to resist disruption of interference from task-irrelevant stimuli or impulsive responses (Friedman & Miyake, 2004, 2017; Miyake et al., 2000). It was suggested that all types of EF rely on WM, i.e., maintenance and manipulation of information concurrently, to an extent (Miyake et al., 2000).

Figure 1.5

Latent Variable Model of Executive Function (Miyake & Friedman, 2017). The Numbers Represent the Correlations Between the Functions and Their Associated Experimental Tasks.



The three EFs identified by Miyake and colleagues (2000) are not considered to be a comprehensive list but are frequently cited by other researchers (Smolker et al., 2014; Scharinger et al., 2015; Glisky et al., 2020). Latent variable analysis was the proposed solution for removing the influence of unreliability and task impurity. It was noted that the three aforementioned EFs demonstrated significant correlations with one another such that none of the factors could be removed without affecting the fit of the latent model. In other words, a three-correlated factors model was most appropriate given that the correlations between latent variable EFs were much higher than individual-task correlations. Miyake and Friedman (2017) describe that ‘diversity’ aspect is captured by the Updating-Specific and Shifting-Specific factors. The interdependence (‘unity’) of functions suggests that they rely on a central executive. The demands on one function may adversely impact the processing resources available for other functions. It is still contested whether the Inhibition factor is specific to inhibiting tasks (Miyake & Friedman, 2012) or reflects a Common EF supporting inhibition and goal maintenance (Munakata et al., 2011).

Table 1b
List of Experimental Tasks Associated with Specific EF Adapted from Miyake & Friedman (2017)

Updating	Inhibition	Shifting
Tone monitoring task	Stroop task	Number-Letter tasks
Keep track task	Flanker task	Colour-Shape tasks
Letter memory task	Anti-saccade task	Category-switch tasks
Spatial 2-back task	Simon task	
	Go/ No-go task	

The main challenge faced by many researchers is the unavoidable characteristic of EF tasks: task impurity. It has been difficult to disentangle the involvement of lower-level processes in any given EF task from the EF of interest (Jacoby, 1999). For instance, the Stroop task has been assumed to measure inhibitory control, but MacLeod and his colleagues (2003) were critical of how inhibition is defined in the Stroop effect. Certain tasks have been found to correlate more strongly with specific EFs than others. Inhibitory control tasks include the Flanker task (Eriksen & Eriksen, 1974), anti-saccade tasks (Munoz & Everling, 2004), Simon task (Hommel, 2011) and go/no-go tasks (Cragg & Nation, 2008). Tasks which load onto the Updating function are the tone monitoring task, keep track task and letter memory task (Miyake et al., 2000). Interestingly, Miyake and colleagues (2000) demonstrated that the operation span task, often associated with WM capacity, was highly correlated with updating tests. Other studies have corroborated the idea that the performance observed in complex span tasks (e.g., n-back) is influenced a person's capacity to control the input and to update WM representations (Engle et al., 1999; St Clair-Thompson & Gathercole, 2006). It is beyond the scope and interest of this thesis to describe every EF task in detail. There are reviews which are dedicated to particular methodological issues and classifications of EF tasks (Alvarez & Emory, 2006; Chan et al., 2008; Miyake & Friedman, 2017). The approach taken in measuring EFs is not as clear-cut as the measurement of WMC, but this does not mean that either approach is more "correct" (McCabe et al., 2010).

Other researchers such as Doebel (2020) have questioned the three-factor model and considered the approach to be reductive. The reasons cited include the lack of far transfer (i.e., improvements) from lab-based EF training to other domains (Kassai et al., 2019) and weak correlational relationships between lab measures of EF (especially when only a single measure is provided, e.g., Devine & Hughes, 2014). Doebel (2020) reiterated that latent variable analyses have revealed separable components which may reflect common task demands rather than the intrinsic structure of EF. For example, all updating tasks will involve the monitoring and replacement of information. The number of EF components can vary across populations, i.e., between children and adults. A recent review has found models of EF are a poor fit for the data from the aforementioned populations (Karr et al., 2018). Doebel's (2020) view was borne from a developmental psychology perspective since it is unlikely that a child would have an inhibitory process which is applicable across various situations. It is more effective for a child to consider previous knowledge of situation in service of a specific goal (e.g., negative experience of being hit to avoid hitting a playmate who had taken their toy). To improve ecological validity, factors such as knowledge, beliefs and values which support goal-related behaviour should be considered. Perone and colleagues' view (2021) of a *dynamic* reconceptualisation of EF development only differs from Doebel's (2020) in that goal-related information and knowledge mutually interact (rather than activate), resulting in goal-directed behaviour. Whilst Doebel's (2020) theory focused on the development of EF, Perone and colleagues (2021) have stated that goal-directed behaviour is important for daily life across the lifespan.

1.4 Methodology

Modified Delayed Match to Sample Task

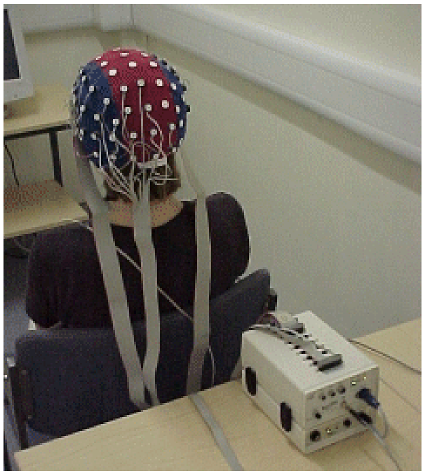
The experimental paradigm of choice for this thesis was a modified version of a visual WM task known as the delayed match-to-sample (DMTS) task, which is considered to be a variant of the Sternberg WM task (Sternberg, 1969). The DMTS task allows the examination of separate cognitive processes delineated in time i.e., encoding, maintenance and retrieval (Kim, 2019). A standard DMTS sequence is as follows: the observer needs to remember an initial stimulus (sample), there is a delay period when the sample is not visible, and the observer must indicate upon the onset of a second stimulus probe regarding the match or mismatch with the initial array. Several stages of processing occur in both the absence and presence of stimuli: a state of expectation can precede the display of to-be-remembered items; encoding of the items follows the presentation of the array; the delay period necessitates maintenance of the items in mind, in WM; finally, presentation of the probe requires retrieval of the relevant item(s) from memory, as well as comparison to the probe, decision-making and responding. All of these stages are important in determining memory performance outcome, and all benefit from selective and focused processing (Gazzaley & Nobre, 2012). Furthermore, making only a subset of array items relevant to the task can intensify pressures for selective processing, i.e., introducing distraction. Some researchers have advocated the benefits of delineating stages in memory such that the maintenance stage engaged the prefrontal cortex (Rypma & D'Esposito, 2000; Cairo et al., 2004; Habeck et al., 2005) whilst others found minimal involvement of prefrontal areas (Beatty et al., 2015; Majerus et al., 2013; Murty et al., 2011). A diverse pattern of results is unsurprising based on the premise that variations of different stimuli, procedures, and analytic methods were used which leaves a degree of uncertainty surrounding which specific brain regions reliably contribute to different WM phases (Kim, 2019). The modifications of the DMTS task in the thesis were as follows: a distractor array was inserted in the retention interval (between the initial stimulus sample and probe array), a manipulation was added in which the pop-out distractor object matched or mismatched the initial stimulus sample, and WM load was operationalised as the number of objects to be encoded in WM (low load with 1 item whereas high load with 4 items). The reason for this modification was discussed in greater detail in Chapter 2 of the thesis (please see section 2.1.3).

Electroencephalography

Electroencephalography (EEG) is a non-invasive method of measuring and recording electrical activity from the cerebral cortex through the scalp. A typical EEG setup requires the use of 64 electrodes being the most common (Figure 1.6), whereas other EEG systems may allow up to 256 electrode channels (Oostenveld & Praamstra, 2001). Standardized electrode placement montages have been developed such as the International 10-20 system and applied in clinical and non-clinical settings (Jasper, 1958). The 10-20 system ensures proportional placement of electrodes and neural activity from prefrontal, frontal, temporal, central, occipital and parietal areas of the brain can be simultaneously extracted (Khazi et al., 2012). Measurements of 'landmarks' such as from the indented area between the eyes to the crest point at the back of the head: (nasion to inion) and left to right pre-auricular points are taken to determine the position of the midline electrode Cz (Handy, 2005; Khazi et al, 2012). A general principle of EEG is that each recorded channel reflects the difference of electrical activity between two positions on the head with one of them being the reference electrode (Jackson & Bolger, 2014). The general rule is that some sites on the head are supposedly less active than others, and sites with less activity would serve as a better reference positions than sites with more activity (Hageman et al., 2001). For instance, it is assumed that areas such as the ears or mastoids do not induce any electrical activity, although there may be no truly neutral location on the human body (Nunez et al., 1997). Thus, the choice of a reference electrode is important, and the most optimal choice remains widely debated because both the evoked and spontaneous potentials of neural activities are influenced by the reference (Teplan, 2002). Event-related potentials (ERPs) are broadly understood as changes in scalp-recorded voltage which are time-locked to a specific event that can be sensory, motor or cognitive related (Luck, 2012). The activity that is detected reflects a summation of activity from a population (approximately thousands) of similarly oriented cortical pyramidal neurons which fire in synchrony in response to stimuli (Sur & Sinha, 2009). EEG provides excellent temporal resolution, which can be quantified in milliseconds and is an appropriate tool for studying the time course for mental processes like memory and selective attention (Teplan, 2002). ERPs are averaged waveforms from multiple trials, consisting of several positive and negative deflections which are considered as early ‘exogenously’ triggered within 100ms post-stimulus or ‘endogenously’ driven, occurring at a later stage in the information processing stream. Endogenous processes are triggered by the stimulus (e.g., visual salience) while exogenous processes are controlled by an individual’s goal-driven intentions (Theeuwes, 2004). The assumption is that any task-unrelated brain activity should average to zero. At least four different measures can be derived from an ERP waveform: amplitude, latency, phase and frequency. Examples of commonly studied ERPs are the early visual processing components P1 and N1 as well as the P300 involved in stimulus evaluation (Woodman, 2010; Luck 2012).

Figure 1.6

Electrode cap placement on a seated participant. The cap is attached to an amplifier which makes the recorded data (signals) more visible. Image retrieved from Biosemi.com.



EEG recordings are not exempt from methodological issues, especially in relation to the spatial resolution of around 5-9 centimetres from the signal source within the cortex (Nunez et al., 1994). The term "volume conduction" is used to describe the issue of recording electrodes being placed at a distance, a few centimetres, from their source generator (Rutkove, 2007). Consequently, the electrical current must pass through layers which have different levels of conductivity (Ollikainen et al., 1999), such as the skull, which can induce a blurring effect on the signal at scalp level (Srinivasan et al., 1996). The recorded activity at each scalp position is a mixture of the underlying brain sources (Makeig et al., 1996). This is not a problem specific to ERPs and applies to other EEG activities of interest, e.g., time-frequency analysis and spectral analysis (Vidal et al, 2015). More modern techniques have attempted to circumvent the *inverse* problem of localizing the sources of the EEG from measurements of the scalp potentials but with varying success (Grech et al., 2008). Electrodes are also susceptible to artifacts, which can distort the true signal resulting from ocular, muscle, skin, movement and instrumental sources (Islam et al., 2016). Some examples include eye movements, jaw clenching, cable movement and sound interference. There are sophisticated and well-established methods of artifact removal algorithms such as independent component analysis (ICA: Makeig et al., 1996) in addition to visual inspection. ICA is a statistical method which uses linear decomposition to determine a set of independent components within the EEG signal (Makeig & Onton, 2011). Components which are usually regarded as artifacts are those with strong activity centred over frontal or temporal electrodes due to close proximity of the electrodes to the eyes and ears and strong activity from a single electrode (Delorme & Makeig, 2004). The removal of components rather than entire trials enables more data to be preserved, although the selection of what constitutes as an artifact is a subjective decision made by the researcher.

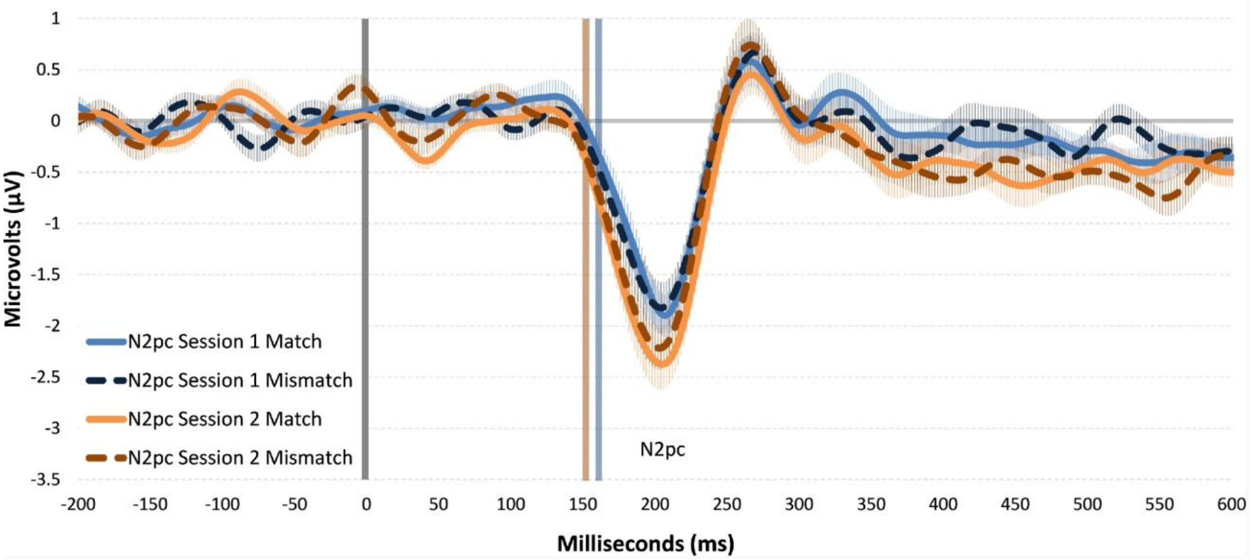
Neural Correlates of Selective Attention

The Posterior Contralateral N2 Component (N2pc)

One of the most extensively studied ERPs in attentional processing is the N2pc component (Figure 1.7). Several studies have supported the role of the N2pc to reflect the attentional selection of potentially relevant items among distractors in visual search tasks via target enhancement or distractor suppression processes (Hickey et al. 2006; Theeuwes, 2010; Woodman & Luck, 1999; 2003). The N2pc component is characterized as an enhanced negativity over posterior scalp electrodes contralateral to the side of an attended stimulus. Maximal around electrode PO7 for targets in the right visual field and PO8 for targets in the left visual field (Jolicœur et al., 2008), the N2pc component can be observed approximately between 150 and 300 ms after the onset of visual stimuli presentation (Luck, 2012). Both bottom-up (e.g., distractor salience; Luck & Hillyard, 1994; Hickey et al., 2006) and top-down (e.g., task relevance; Eimer, 1996; Eimer & Kiss, 2008; Lien et al., 2008; Mazza et al., 2009; Wykowska & Schubo, 2011) factors have been found to influence attentional capture.

Figure 1.7

The N2pc Component Illustrated by Fuggetta & Duke (2017). The Difference of Grand Average Waveforms (contralateral minus ipsilateral) is Depicted.



The *signal suppression* hypothesis has been proposed to resolve the bottom-up/top-down debate (Sawaki & Luck, 2010; Gaspelin & Luck, 2019) and states that suppression is guided by pre-attentive feature information which is a common characteristic in visual search models (Luck & Hillyard, 1994). The signal suppression hypothesis is in agreement with stimulus-driven theories which assume that salient colour singletons will automatically capture visual attention. However, there is a top-down inhibitory mechanism which suppresses the item before the initial shift of attention (Gaspelin & Luck, 2018). In relation to the N2pc component, this theory incorporates previous findings which have investigated the Pd (distractor positivity) component, a contralateral positivity elicited by distractor stimuli as evidence for suppression (Eimer & Kiss, 2008; Kiss et al., 2012; Sawaki & Luck, 2012; Gaspelin et al., 2017). The time window of Pd is very broad, approximately 100-440 ms depending on the task and stimuli (Hickey et al., 2009). Furthermore, the N2pc component may also comprise of an electrophysiological index of target processing with contralateral negativity (Nt) followed by positivity (Pt) to the target hemifield (Bretherton et al., 2020). Gaspelin and Luck (2019) have recently reviewed the evidence that salient distractors can be inhibited especially with learning.

The Anterior P2 Component

The anterior P2 component has been found to reflect the automatic detection of pop-out stimuli in target-detection tasks (Luck & Hillyard, 1994; Fuggetta & Duke, 2017). It has been previously found that the anterior P2 wave is larger for target pop-outs compared to non-target pop-outs and homogeneous arrays (Luck & Kappenman, 2012). The occurrence of a P2 waveform is influenced more by the presence of a specific and relevant feature more than irrelevant features within a visual array (Luck, 2012), remaining insensitive to stimulus frequency (Potts et al., 1996). The time window for this component is around 180-300ms, and the component is visible over prefrontal recording sites (Potts, 2004).

Sustained Posterior Contralateral Negativity (SPCN)

This lateralized ERP component is interchangeably known as contralateral delay activity (CDA), referred to SPCN in this thesis, and often follows the N2pc component (Dell'Acqua et al., 2006; Holmes et al., 2009; Luria et al., 2016). The SPCN component can appear 300-650ms after stimulus presentation and persists for the duration of a task's retention interval (Jolicœur et al., 2006; 2008). The CDA has been associated with several aspects of visual WM such as WM capacity (i.e., the number of representations held; Vogel & Machizawa, 2004; Luck & Vogel, 2013; Kang & Woodman, 2014), the maintenance of visuospatial attention (Jonides et al., 2008) and the filtering of information (Vogel et al., 2005). Additionally, McCollough and colleagues (2007) found that the amplitude of SPCN was lower on incorrect response trials as opposed to correct trials but was unaffected by low-level visual features like the distance between visual objects. Another study has suggested that the Pd may reflect distractor suppression during the resolution of target processing (Hilimire et al., 2011).

Transcranial Magnetic Stimulation

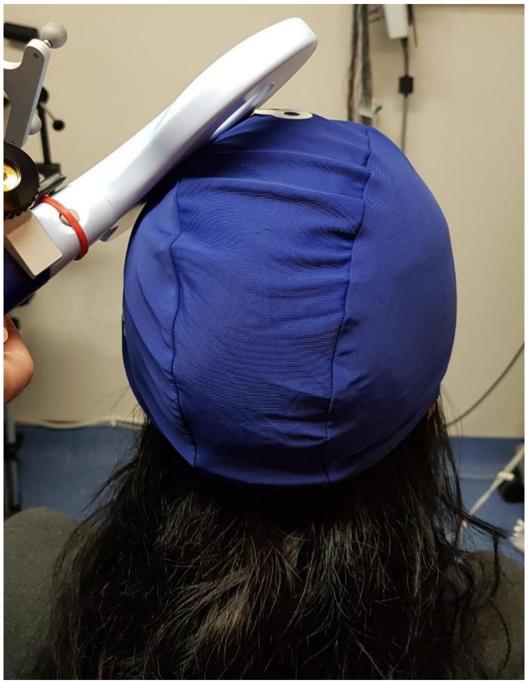
Transcranial Magnetic Stimulation (TMS) is a non-invasive and safe brain stimulation technique introduced by Barker and colleagues (1985). TMS operates using the principles of electromagnetic induction based on Faraday’s Law (1831), and this induction produces electrical currents to stimulate underlying neural tissue (for a recent review, see Ziemann, 2017). The stimulation is applied using a magnetic coil which generates a high-intensity magnetic field via a rapid electrical current (Hallet, 2007). A large current (up to 2 Tesla) is induced in a short period of time with the duration of the magnetic field lasting around 0.3 milliseconds (Toga & Mazziota, 2002; Hallett, 2007). Although there are various kinds of TMS coils, the figure-of-eight “butterfly” coil is predominantly used because it is focal. TMS focality is expressed in centimeters squared as a measure of cortical surface, and a butterfly coil is able to stimulate 1-2cm^2 squared beneath its central junction (Sandrini et al., 2011). In a butterfly coil, the current is maximal at the intersection of the two circular coils. The depth of stimulation does not reach subcortical structures such as the basal ganglia and thalamus directly (Strafella et al., 2005; Fuggetta & Noh, 2013).

TMS can be administered at different times with respect to a task: which can be either with an “online” or “offline” approach (Luber & Lisanby, 2014). The online approach allows direct observation of TMS effects on brain tissue in real time during a task (trial by trial). On the other hand, “offline” TMS approaches would stimulate at a low frequency (usually 1Hz) with longer trains of stimulation (Sandrini et al., 2011). Offline TMS protocols are useful in instances where the aim is to observe temporary effects on perception (e.g., Roberston et al., 2003) or in conjunction with other neuroimaging methods, e.g., fMRI (Siebner et al., 2009). TMS can be viewed as introducing interference to the processing of information by disrupting task performance (Walsh & Cowey, 2000) with a historical interpretation of TMS as a short-lasting “virtual lesion” (Walsh & Rushworth, 1999) to mimic the effects of a brain lesion without the cortical reorganisation. The virtual lesion analogy was not very informative in terms of characterising the mechanisms of action of TMS (Miniussi et al., 2013) because it was equally possible for the effects of TMS to have acted as suppression of neural signals or as the addition of random neural activity (Harris et al., 2008; Ruzzoli et al., 2010). A more modern-day interpretation of TMS effects is through the “state dependency” concept which is the consideration of the initial state of the neural region prior to the administration of TMS (Silvanto & Pascual-Leone, 2008). The concept of state dependency is linked to the timing of TMS because it is assumed that populations of neurons are at a baseline level and will be equally facilitated when TMS is applied before the onset of a cognitive process (Silvanto & Pascual-Leone, 2008). If TMS is applied during a cognitive process, different populations of neurons will be differentially activated resulting in an imbalance of activity i.e., noise in neural processing and possibly disruption to observed behaviour (Silvanto et al., 2007). Although it has been argued that TMS is more appropriate for investigating sensorimotor processes which are more rapid in nature, it is possible for TMS to interfere with prolonged cognitive processes such as covert spatial orienting, by interrupting the parietal cortex at specific time points (Chambers et al., 2004; Rushworth & Taylor, 2006).

TMS can be delivered as a single pulse or a train of repetitive pulses (rTMS) ranging from 1-50 Hz (Walsh & Rushworth, 1999) with 0.1 to 1 Hz being low-frequency and above 1Hz being high-frequency (Fitzgerald et al., 2006). In several studies specific to visual search and working memory (Taylor et al., 2007; Muggleton et al., 2010; Lane et al., 2012), high frequency rTMS is usually delivered at 10 Hz for 500 ms, so five pulses were delivered within half a second. In contrast to single pulse TMS, the changes and modulations of cortical activity induced by rTMS can outlast the stimulation period (Siebner & Rothwell, 2003; Klomjai et al., 2015). The after-effects of rTMS can be inhibitory at low frequencies (usually under 1 Hz) or excitatory effects at higher frequencies i.e., over 5 Hz. It has been found that inhibitory after-effects of high frequency rTMS were reversed in low-intensity protocols (below MT) but still increase cortical excitability at high intensity (greater than MT). In studies which have investigated WM, both single-pulse TMS (Mull & Seyal, 2001; Oliveri et al., 2001; Mottaghy et al., 2003) and rTMS (Pascual-Leone & Hallett 1994; Kessels et al., 2000; Mottaghy et al. 2000; Mottaghy et al., 2002) protocols have been implemented. A single pulse of TMS over the primary motor cortex (M1) allows for the recording of a motor-evoked potential (MEP) amplitude and causes a contraction in contralateral muscles corresponding to a visible twitch in the target muscle/hand (Rossini et al., 1994; Rothwell et al., 1999). The amplitude of evoked potentials detected with surface electromyography (EMG) electrodes indexes the excitability level of the corticospinal pathway (Rothwell et al., 1987). The MT is usually defined when the target muscle is active or at rest with a majority of researchers adhering to the *relative frequency* method: a starting intensity is not specified (Rossini et al., 1994). There is a criterion that requires at least 5 out of 10 pulses applied during a rested state require an MEP amplitude > 50 µV (Rossini et al., 1994). The stimulation intensity can then be adjusted to the minimum intensity that can evoke the ‘twitching’ response. A clear demonstration of a short-term effect by administering single TMS pulses over the occipital cortex is the generation of phosphenes, the phenomenon of perceiving light without light entering the eye (Ro et al., 2004; Nevler & Ash, 2015). The length of TMS effects on different kinds of cortical tissue and functions can fluctuate, for example, the disruption in hand muscles from a single TMS pulse can last for 200ms over the motor cortex, whereas interference to visual perception was approximately 70-140ms (Bolognini & Ro, 2010). The stimulation intensity of TMS is usually determined with respect to an individual's motor threshold (MT) to account for the variability in the length of temporal windows as a result of disruption by TMS (Bolognini & Ro, 2010). Single pulse TMS is considered to be safe, whilst rTMS protocols carry a risk of causing seizures in healthy participants though this is an extremely rare occurrence (Rossi et al., 2009). Rossi and colleagues (2009) have described potential risks associated with the application of TMS in great detail. The authors have developed a safety guideline questionnaire disseminated for widespread use to screen rTMS candidates. The requirements for screening candidates are not absolute contraindications to TMS, but researchers should be cautious in balancing the risk/benefit ratio. For example, part of the screening criteria would pertain to the person's history of seizures, hearing problems and whether there is any metal implanted in their body (Rossi et al., 2011).

Figure 1.8

Placement of a Magnetic Coil Placed Tangentially to the Scalp.



TMS-EEG: A Combined Method

TMS is an intervention technique that is commonly applied to a single target area at a time and cannot capture the effect of the intervention across the entire brain (Miniussi & Thut, 2010). In contrast, EEG is able to address this issue because signals are captured from multiple regions of the brain which allows for the examination of TMS effects (timing / sequencing) beyond the area of interest. There are three main ways of applying TMS-EEG; 1) an *inductive* method of measuring at the level of cortical reactivity and connectivity across experimental conditions, 2) *interactive* method of assessing how, when and where TMS affects a particular functional network in the brain engaged in a cognitive task and 3) a *rhythmic* approach of examining oscillatory brain activity i.e., causal relationships between cortical rhythms and cognitive, perceptual and motor processes (Komssi & Kähkönen, 2006; Taylor et al., 2008; Thut & Miniussi 2009; Miniussi & Thut, 2010; Casula et al., 2013). In relation to the application of the TMS-EEG technique in studies concerned with visual attention, TMS delivered to fronto-parietal areas induces a disruptive effect on attentional modulation (Fuggetta et al., 2006; Kehrer et al., 2009; Taylor & Thut, 2012).

Initial studies combining TMS with concurrent EEG had to overcome a series of methodological hurdles. For example, saturation of the amplifier system due to the large electrical signal produced by TMS and could even potentially damage the amplifier system (Taylor et al., 2008). Other methodological issues to consider were the overheating of electrodes which can be resolved by using small Ag/AgCl pellet electrodes and loud click sounds from TMS and sensations on the skin induce auditory/somatosensory artifact noise which may be mistakenly interpreted as TMS-evoked activity (Illmoniemi & Kičić, 2010). Another vital factor to consider is the placement of the TMS coil given that a movement of 5mm between experimental conditions results in large changes in the evoked EEG signals (Komssi et al., 2002). The introduction of stereotaxic neuro-navigation systems (SNS) alongside TMS has been beneficial for localizing precise sites of stimulation (e.g., Schonfeldt-Lecuona et al., 2005). In non-clinical research settings, the neuro-navigation system is estimated based on an MRI-constructed template based on an individual’s facial/cranial landmarks. Frameless stereotaxic systems for TMS require the subject’s head MRI data and coil geometry to track the coil position relative to the subject’s head (via a sensor) and register this in MRI space. An advantage of using such a system, the stimulation site of interest as well as coil position and orientation can be monitored in real time (Illmoniemi & Kičić, 2010).

1.5 Neural Basis of Executive Function

A concept that is central to the selective attention literature is executive function which has been considered to encompass a variety of cognitive functions driven by behavioural goals (Mackie et al., 2013) inclusive of WM (D'Esposito & Postle, 2015). Behavioural research can often reach the conclusion in support of either early or late selection of attention. One way of understanding how attention is modulated by WM load is by investigating the temporal dynamics of signal enhancement/noise suppression (Serences & Kastner, 2014) given that inhibition is more directly observable from a neurophysiological perspective (Aron, 2007). With advances in neuroimaging techniques, there are more opportunities to determine which neural regions are more causally associated with cognitive processes than others (Hallett, 2007). The purpose of this section is to introduce growing evidence for the role of the dorsolateral prefrontal cortex (DLPFC) and posterior parietal cortex (PPC) in selective attention and WM functions in the visual domain (Knudsen, 2007; Berryhill, 2012; Brunoni & Vanderhasselt, 2014). It is worth noting that these regions are commonly grouped together, due their strong interconnectivity, as the "fronto-parietal attentional network" (FPN: Katsuki & Constantinidis, 2012; Scolari et al., 2015). The dorsal regions comprise of the PPC, premotor and prefrontal cortex which are connected along fibers bundles passing through the superior longitudinal fasciculus (Ptak, 2012). There are complications surrounding EF as a framework for localization of function in the frontal lobe (Stuss & Levine, 2002) as previously mentioned. There is a particular focus on studies with healthy young adults using electroencephalography (EEG) and transcranial magnetic stimulation (TMS) as the main methodologies. Other neuroimaging methods and studies concerning clinical samples or other populations with may be referenced where relevant. The reason for a particular focus on human neuroimaging studies because there is difficulty in transposing precise localization of WM functions from monkeys to humans due to large-scale interspecies anatomical differences (Petrides et al., 2012). For instance, there are no clear homologues for regions of the human PPC in comparison to macaques (Orban et al., 2004).

The prefrontal cortex (PFC) represents a large area of the brain which is approximately a third of the entire human cerebral cortex (Siddiqui et al., 2008), inclusive of the frontal eye field. It is still not known what the specific functional contributions of the PFC are although some researchers have attributed an operational role for the PFC such as dynamic filtering (Shimamura, 2000), adaptive encoding (Duncan, 2001), by linking it to the central executive component in Baddeley's model of WM (Funahashi, 2017) or an integrative model which acknowledges the PFC's contribution in the representation of information (Miller & Cohen, 2001). Traditionally, studies which have demonstrated the involvement of the PFC in the control of cognitive processes have primarily focused on normal WM functioning such as memory maintenance (Eriksson et al., 2015). Sustained neural activity in the PFC was observed during the delay period of a WM task and an intact lateral PFC was crucial for normal performance in delayed-response tasks. Similar findings were observed in monkeys (Goldman & Rosvold, 1970; Funahashi et al., 1989) and humans with PFC lesions (D'Esposito & Postle, 1999). Findings from animal models alluding to the dorsal/ventral dissociation (Ungerleider & Mishkin, 1982) of different streams for processing spatial (dorsal: "where") versus object (ventral: "what") information have been investigated in human neuroimaging studies related to attention and WM (Levy & Goldman-Rakic, 2000; Corbetta et al., 2008; Kehrer et al., 2009). Corbetta and Shulman (2002) proposed that the FPN of attention can be divided into discrete networks; i.e., dorsal and ventral. In their review, the dorsal FPN functions as the top-down control centre which generates and maintains endogenous signals based on current goals and preexisting knowledge about stimulus features and locations to the sensory cortex. Indeed, research supporting this notion has been demonstrated in relation to response preparation (Astafiev et al., 2003), expectation of seeing a target stimulus presented at a particular spatial location (Hopfinger et al., 2000), filtering of distractors via top-down suppression (Chadick et al., 2014). In contrast, the ventral FPN works in conjunction with its dorsal counterpart during instances of target detection (Corbetta et al., 2000), independent of expectations or task preparation. Both the dorsal and ventral networks are activated during the reorienting of attention especially when a target unexpectedly appears at another which differed from the anticipated location (Kincade et al., 2005; Vossel et al., 2006) or was infrequently presented (Bledowski et al., 2004). Vossel, Geng and Fink (2014) are also in agreement with the idea that the ‘ventral’ and ‘dorsal’ attentional networks may not work in isolation. Wager and Smith (2003) found the expected dorsal-ventral dissociation for the storage of spatial and non-spatial information exclusively in the posterior cortex. The inferences drawn from neuropsychological studies must be interpreted with caution because functional magnetic resonance imaging studies (fMRI) alone only provide an associative relationship between a cognitive process and a broad brain region (D’Esposito et al., 2000).

Dorsolateral Prefrontal Cortex

The dorsolateral prefrontal cortex (DLPFC) has been defined as functional structure occupying the lateral parts of Brodmann areas 46 and 9 in the middle frontal gyrus of humans (Boschin et al., 2017). The DLPFC has been implicated in classic neuroimaging studies in primates where its presumed role was to be temporary storage for sensory information (Goldman-Rakic, 1987; Funahashi et al., 1989) or abstract rules and task contingencies (Miller & Cohen, 2001) and in humans (Curtis & D’Esposito, 2003; Balconi, 2013; Funahashi, 2015) through observations of persistent neural activity in delayed response tasks. In this view, the sustained activity in the DLPFC reflects some maintenance or top-down process rather than the storage of representations, which reside in more posterior areas (Petrides, 2000; Miller & Cohen, 2001; Curtis & D’Esposito, 2003; Gazzaley et al., 2007). The anatomical interconnection between the prefrontal and posterior cortices has been exemplified in the work undertaken in spatial cognition (Goldman-Rakic, 1988), visual selective attention (Squire et al., 2013) and VWM (Liesefeld et al., 2014). Liesefeld and coauthors (2014) identified a clear sequence of events in VWM with the filtering of distractors mainly driven by prefrontal areas which inhibited the parietal storage of irrelevant objects. The DLPFC has been implicated in studies which have tapped into executive control behaviour such as adapting to a changing environment, overriding habitual responses or shifting attention between tasks (Miller & Cohen 2001; Passingham & Sakai, 2004).

In contrast to fMRI studies, non-invasive brain stimulation techniques used in studies specifically targeting the DLPFC regions have established a causal role in visual WM performance and memory-guided responses (Postle et al., 2006; Hamidi et al., 2009; Preston et al., 2010; Zanto et al., 2011; Feredoes et al., 2011; Kehrer et al., 2015; see meta-analyses by Brunoni & Vanderhasselt, 2014; Kim, 2019). Feredoes and colleagues (2011) employed a combined transcranial magnetic stimulation (TMS)-fMRI design to evaluate the right DLPFC's involvement in visual WM. The authors found evidence in favour of a top-down control mechanism localized to the DLPFC in successful maintenance of relevant information amidst distraction during a delay period. The absence of significant TMS effects in the absence of distraction implies that the DLPFC is not always required for simple memory maintenance and instead was recruited to overcome distraction present in the visual scene via sensory gating (Postle, 2005). The effects of TMS were not equivalent across conditions thus the data was interpreted that the influence of DLPFC on posterior regions were dynamic. The selectivity of the DLPFC to be engaged in situations with distractors present is in agreement with the adaptive coding account of DLPFC function (Duncan, 2001). In this view, control signals from the DLPFC are disseminated to posterior areas which represent information specific to targets (Egner & Hirsch, 2005).

Parietal Cortex

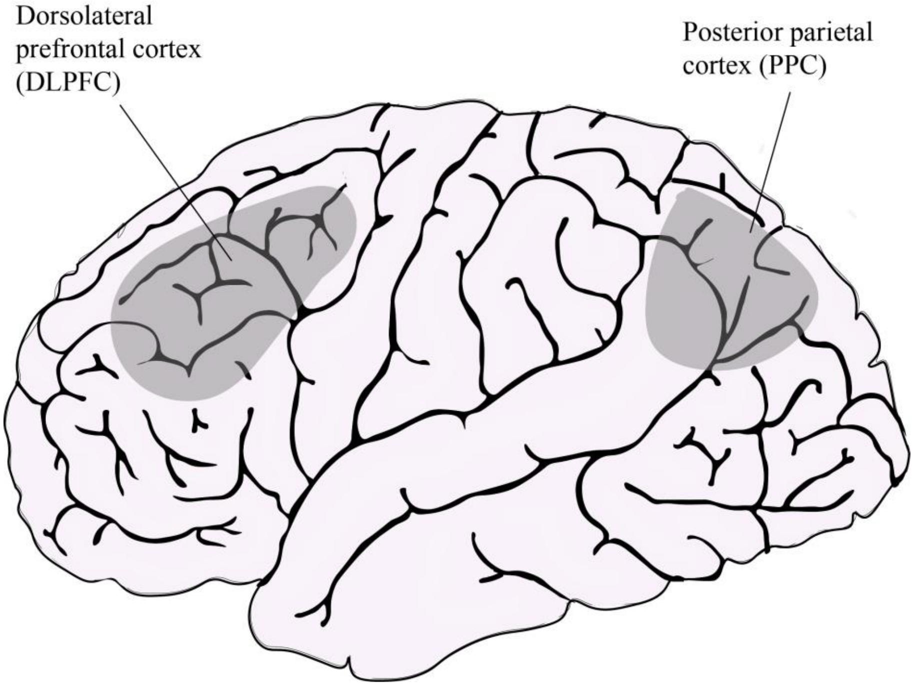
The parietal lobe encompasses 20% of the human cerebral cortex and comprises of two major areas; the posterior parietal cortex (PPC) and the somatosensory cortex (Behrmann et al., 2004). The PPC is a large area which covers cortical regions such as the superior parietal lobule (SPL, BA 5 & 7) and the inferior parietal lobule (IPL, BA 39 & 40) inclusive of the angular and supramarginal gyri (Berryhill, 2012). The PPC has been deemed as the "association" cortex because of its location, whether directly or indirectly, at the intersection of multiple sensory regions i.e., visual, auditory and tactile cortices such as those related to eye movements (Ashbridge et al., 1997). There has been evidence for the involvement of the PPC in a variety of cognitive operations such as selective attention (Husain & Nachev, 2007; Driver et al., 2010; Corbetta & Shulman, 2011), spatial (Silver et al., 2005; Chiu & Yantis, 2009; Greenberg et al., 2010) and non-spatial (Giesbrecht et al., 2003; Yantis & Serences, 2003; Tamber-Rosenau et al., 2011) visual attention, visual perception (Berman & Colby, 2009), action planning and control (Tunik, Rice, Hamilton & Grafton, 2007), reorienting (Corbetta et al., 2008) and executive function (a meta-analysis by Niendam et al., 2012) amongst others. The link between the PPC and memory is not as clear-cut partly due to studies of neuropsychological patients with PPC damage that is not uniform across different individuals who do not exhibit major memory deficits (Berryhill, 2012).

In a paper by Olson and Berryhill (2009), the evidence for the 'surprising' link between the PPC to human memory was reviewed. There was a particular focus on VWM, and they evaluated separate mnemonic roles played by the PPC such as information manipulation or via the internal attention model. The information manipulation interpretation was supported, particularly inferred from activations in the SPL when the manipulation of information in WM was required (Wendelken et al., 2008). There has been evidence for the involvement of SPL areas in other manipulation tasks such reordering sequences of stimuli (Wager & Smith, 2003; Marshuetz et al., 2006) and solving mathematical equations (Dehaene et al., 2004). However, this was not the strongest interpretation because greater activations in brain areas can be attributed to differences in levels of difficulty in a task compared to a baseline condition. In addition, the information manipulation hypothesis has been undermined by findings of PPC activations in studies which have used WM maintenance tasks without any manipulation demands (Todd & Marois, 2004, 2005; Xu & Chun, 2007; Hamidi et al., 2008). The internal attention model by Berryhill, Chein and Olson (2011) proposes that the PPC serves to prevent WM representation(s) from decaying via *attentional refreshing.* This refreshing mechanism and attention-based storage is not modality specific and only items within the focus of attention will benefit from the covert maintenance. This is aligned with attention-based models of WM such as the Embedded Processes Model (Cowan, 1999). This proposal has received support from Chein and Fiez (2010) who found that the memory recognition processes drew upon the PPC whereas recall processes did not.

The historical approach to TMS was by inducing "disruption" to the PPC regions in healthy individuals (Weissman-Fogel & Granovsky, 2019). This virtual lesion technique was deemed analogous to mimic visuospatial deficits frequently encountered in neglect patients without the actual cortical reorganization (Fierro et al., 2000; 2001; Hilgetag et al., 2001; Bjoertomt et al., 2002). A vast majority of TMS studies which have specifically targeted the PPC has uncovered its critical role in spatial attention necessitated by conjunction search and change blindness tasks (Corbetta & Shulman 1998; Hilgetag et al., 2001; Shafritz et al., 2002; Ellison et al., 2003; Chambers et al., 2004; Beck et al., 2006; Fuggetta et al., 2006). In terms of non-spatial selection, Mevorach and colleagues (2006) found a difference between the hemispheres in that the right PPC drew attention towards a salient event whereas the left PPC directed attention toward targets of lower salience. The authors employed a repetitive TMS (rTMS) protocol which disrupted the processing of saliency dimensions. Other researchers have revealed further functional distinctions within the PPC. For example, Pollmann and colleagues (2003) postulated that the SPL is involved in visual marking and distinguishing old distractor items to bias the selection of new objects during visual search. However, activation in a certain brain area does not imply a causal role in a specific cognitive function. Nonetheless, the consensus is that parietal areas are crucial when people are reorienting attention or movements and such representations must be updated (Rushworth & Taylor, 2006).

Figure 1.9

Lateral View of Dorsolateral Prefrontal Cortex and Posterior Parietal Cortex.



Right-Hemispheric Dominance within the Dorsal Fronto-Parietal Network

On one end of the debate, some authors have advocated purely exogenous processing accounts of attentional control associated with the PPC (Arcizet et al., 2011) whilst it has also been shown to be involved in the top-down control of visual attention (Corbetta & Shulman, 2002). This twofold pattern of findings was found within the PFC as well (Li et al., 2010; Noudoost & Moore, 2011). The DLPFC is a region of the frontal lobes that is most typically associated with EFs including working memory and selective attention (Curtis & D'Esposito, 2003). The predominant view in contemporary literature is that the PPC works in conjunction with the PFC to compute information especially in relation to spatial WM (for reviews; Wager & Smith, 2003; Passingham & Sakai, 2004; Naghavi & Nyberg, 2005; D'Esposito, 2007; Duecker & Sack, 2015). TMS applied to either the PPC or DLPFC during spatial WM maintenance tasks adversely affected response times (Koch et al., 2005, Oliveri et al., 2001). Existing research also recognizes the interplay between the DLPFC and PPC in visual attention. In humans, the most direct route for spatial attentional control across the visual field between the PPC and frontal areas within each hemisphere is via the corpus callosum (Hofer & Frahm, 2006). In a review of TMS studies, there was a tendency for a right-hemispheric dominance within the dorsal fronto-parietal attention network in a majority of the attentional control studies (Duecker et al., 2013; Duecker & Sack, 2015). Nevertheless, the absence of significant effects in the left hemisphere, specifically in the parietal lobe (Fierro et al., 2000; Hilgetag et al., 2001; Bjoertomt et al., 2002) may be due to methodological issues such as imprecise coil localization or the interpretation of null findings (De Graaf & Sack, 2011). In cases where there is involvement of the left hemisphere (Battelli et al., 2009; Szczepanski & Kastner, 2013), the interpretation of effects revolved around competitive interactions between the hemispheres. There are two competing theories of spatial attention which have been frequently cited; Heilman's *hemispatial theory* and Kinsbourne's *opponent processor model*, which can account for asymmetrical findings but differ in the proposed mechanisms (Heilman & Valenstein, 1979, Kinsbourne, 1977; Heilman & Abell, 1980).

There has been much research interest from fMRI studies into attention and executive processes in WM especially the rPPC and the rDLPFC are involved in the neural mechanisms of attentional shifting (Yantis et al., 2002; Wager et al., 2004) and in the context of negative priming (Krueger et al., 2007). With regards to TMS studies, the causal involvement of the rDLPFC and the rPPC in visual search was investigated (Yan et al., 2016; Wang et al., 2018; 2020). Yan and colleagues (2016) dissociated the roles of rDLFPC and rPPC such that TMS pulses applied to the rDLPFC prolonged response times specific to the visual "search" condition, whilst the rPPC was significantly involved in the detection of a "pop-out" target (in contrast to Nobre et al., 2003). Wang and colleagues (2018) have suggested that the rDLPFC sustains a representation of a target and is able to send top–down signals to guide task performance whilst ignoring irrelevant distractors. This pattern of results corroborated the findings from a related EEG study examining the distinct roles of the prefrontal and parietal cortices in the allocation of visual attention for detecting targets (Li et al., 2010). These authors used EEG power analyses (4-24 Hz) and uncovered a double dissociation between the cortices. More specifically, there was increased frequency band in parietal areas for bottom-up control (pop-out targets) and in frontal regions for top-down control (search targets) respectively. Other studies which have targeted the parietal cortex clearly demonstrated a right hemispheric asymmetry with regards to the control of visuospatial attention and visual search (Ashbridge et al. 1997; Fierro et al. 2001; Pourtois et al., 2001; Muggleton et al., 2003; Rushworth & Taylor, 2006; Hodsoll et al., 2009; Ruff et al., 2009; Lane et al., 2012; 2013). RDLPFC appears to be sensitive to WM manipulations and priming effects by associative measures (Braver et al., 1997, Cappell et al., 2010, Huang et al., 2013) and causally (Kehrer et al., 2015; Wang et al., 2020).

Overview of Thesis

The first objective of the thesis was to test the WM load predictions (i.e. under high WM load, there is reduced capacity for prioritisation of targets leading to increased processing of distractors) from *The Load Theory of Selective Attention and Cognitive Control* (Lavie et al., 2004). Research is warranted for understanding the effects of "executive control load" in comparison to the widely studied "perceptual load" effects within this framework. The operationalization of executive control load beyond the simplistic definition of "increasing distractor interference", according to Load Theory, was tested in a behavioural experiment (Chapter 2). Given that WM itself is not a unitary system (e.g. Baddeley & Hitch's WM model, 1974; 2000), it was important to target a specific type of WM load: i.e. updating of visuospatial information. Miyake and Friedman's model of EF (2017) offers delineation of separate functions; updating, shifting and inhibition. The interplay between the **updating:** (continuous monitoring and rapid replacement of working-memory contents) and **inhibition:** (suppression of impulsive or automatic responses) EF was of primary interest. Lavie (2010) states that distractor interference is increased when executive control functions were loaded and acknowledges that dual-task conditions may inflate demands on cognitive control. All three experiments in this thesis investigated attentional capture effects modulated by WM load within a single-task setting via a modified delayed match-to-sample task. The current approach extends previous approaches including Lavie (2010).

The second objective was to examine the electrophysiological markers associated with visual attention and inhibition of distracting stimuli. There is an ongoing debate concerning the extent to which top-down control versus bottom-up influences underlie attentional capture effects. The focus of Chapter 3 was to evaluate suppression as a possible mechanism for attentional capture effects (Gaspelin & Luck, 2019). Electroencephalography as a methodological tool allowed the investigation of a well-established index of attention: the N2pc component. This chapter introduces an alternative theoretical framework: Task-Engagement/Distraction Trade-off (Sörqvist & Rönnberg, 2014) to Load Theory. An additional exploratory analysis was included (Appendix I) to confirm that the novel task was related to self-reported measures of distractibility in everyday life.

The final objective was to address the causal role of the right dorsolateral prefrontal cortex (rDLPFC) and right posterior parietal cortex (rPPC) in WM and selective attention (Zanto et al., 2011) given that there is an asymmetry for right hemispheric dominance in attentional control (Duecker & Sack, 2015). Chapter 4 presents a combined TMS-EEG experiment to establish a causal role for the stimulation sites of interest (rDLPFC and rPPC, Vertex as control) and to examine the time course of WM load effects. However, the EEG data was excluded from the main analysis due to technical issues. Finally, critical evaluation of the thesis with regards to Load Theory and recommendations for the field were the focus of Chapter 5.

Chapter 2: Does Working Memory Load Increase Interference from Distracting Stimuli?

2.1 Introduction

Previous research has established that selective attention and WM are related as these constructs share the same capacity-limited resources and overlapping neural representations (LaBar et al., 1999; Awh et al., 2006; Gazzaley & Nobre, 2012; De Fockert, 2013; Kiyonaga & Egner, 2013). Selective attention refers to the differential processing of concurrent sources of information (Treisman, 1969; Johnston & Dark, 1986; Mangun, 1995; Driver, 2001). WM is characterized as the capacity-limited buffer which allows brief storage and manipulation of information associated with a current task or goal (Baddeley & Hitch, 1974; Baddeley, 2007). In the visual domain, visual WM (VWM) involves retaining information and preventing interference from other inputs whereas visual attention reflects the selection process of objects currently visible in the visual field (Logie, 1989; Luck & Vogel, 1997; Ungerleider et al., 1998; D'Esposito et al., 1999). Therefore, it is likely that both processes contribute to the selective activation and prioritization of particular visual input above others. The idea that WM plays a role in attention is not recent; it is rooted in the biased competition model (Desimone & Duncan, 1995; Desimone, 1998). The authors believed that attentional selection is driven by competition between neural representations. If it is assumed that WM serves to retain information in an accessible state, then the content of WM should modulate effects of attention depending on the match between WM contents and the external environment. The representation of a particular search item, termed as the 'attentional template', is stored in VWM (Bundesen, 1990; Desimone & Duncan, 1995) and may bias the activation of particular features, which results in greater focus of attention for that object. Thus, the active maintenance of an object in VWM results in a competitive advantage such as a bias for objects in the environment which match or were related to the initial sample (Downing, 2000; Moores et al., 2003). Furthermore, the attentional system is arguably inefficient if it is solely driven by bottom-up processes so a top-down feedback mechanism (e.g. an observer’s goals or intentions) serves to highlight which stimulus is most relevant. This model acknowledges that bottom-up processes also contribute to resolving the competition for attention. For instance, a highly salient object will receive priority from attention before top-down influences can be exerted (Reynolds & Chelazzi, 2004; Carrasco, 2011). In this chapter, the main theories that are discussed will be categorized by the nature of the predicted effects on attention, i.e. domain-general (Lavie et al. 2004; Benoni & Tsal, 2010) versus domain-specific (Kim et al., 2005; Park et al., 2007). There will also be discussion of visual WM capacity theories that argue for either a finite pool of resources, unlimited resources or a middle ground (e.g. Vogel & Machizawa, 2004; Bays & Husain, 2008).

In an attempt to isolate the effects of attention from executive functions and WM processes, a framework of attention was put forward by Luck and Gold (2008). Attention can be viewed as two distinct constructs. On the one hand, there is *input selection*, which refers to the selection of relevant information for further processing, whereas *rule selection* encompasses the selective activation of task-related rules. Visual search is considered as an input selection task because an individual would be required to preferentially choose a subset of input for further processing at the expense of other inputs. Input selection is dependent on executive control processes which fine-tune the selection parameters to select the task-appropriate information of to-be attended information and suppress to-be-ignored input. Input selection can further be divided into i) the control of selection and ii) the implementation of selection. The authors likened these two processes to a spotlight metaphor of attention. The former reflects the process of identifying which input should be selected by directing the beam correctly. The latter dictates the extent of differential processing between selected and unselected inputs, i.e. the strength of the beam. Several studies have demonstrated the influence of WM representations in guiding attention, especially under dual-task conditions (Chelazzi et al., 1993; Dalvit & Eimer, 2011; Olivers et al., 2006; Soto et al., 2005; 2006; Soto & Humphreys, 2008; Zhang et al., 2011). In the visual domain, the influence of WM contents on selective attention would be measured by combining two different experimental tasks such as requiring an individual to hold content in WM (e.g. a string of digits), which varies in terms of cognitive demand whilst completing a visual search task. Several studies have reported results in favour of attention being biased towards stimuli that matched the contents of WM (e.g., Soto et al., 2005; Zhang et al., 2011). Soto and colleagues (2005) found that visual search was biased by the contents in WM even if those items were not part of the target template. When an item that was previously held in WM reappeared enclosed in a distractor item, search performance deteriorated compared to displays where it was absent. Other researchers have found results in the opposite direction, i.e., attention being diverted away from a memory-matching distractor in a visual search task (Downing & Dodds, 2004; Woodman et al., 2001; Woodman & Luck, 2007). Downing and Dodds (2004) found very little evidence for automatic memory-driven attentional capture and suggested that target and distractor information can be shielded from each other. One criticism of earlier studies contradicting attentional guidance effects was that WM resources were overloaded (Soto & Humphreys, 2008; Zhang et al., 2011). For example, Woodman and Luck (2007) required participants to perform three tasks: articulatory suppression, visual search and load maintenance. Attentional guidance effects were diminished when WM load was 4 items and close to WM capacity limit (Cowan, 2001; Luck & Vogel, 1997) or 2 items with articulatory suppression (Soto & Humphrey, 2008).

2.1.1 Are Visual Working Memory Load Effects on Selective Attention Domain-General or Domain-Specific?

A concept that is central to the selective attention literature is *cognitive control* which has been considered to encompass a variety of cognitive functions in service of goal-directed behaviour to cope with uncertainty and resolve conflict (Mackie et al., 2013). The term cognitive control encompasses a variety of functions such as working memory (D’Esposito & Postle, 2015) and dual-task coordination (Shallice & Burgess, 1996) often associated with prefrontal cortices (Miller & Cohen, 2001). Most studies investigating how selective attention is modulated by WM load has operationalized load using digit rehearsal (Burnham, 2010; De Fockert et al., 2001; Lavie & De Fockert, 2005) under dual-task conditions which entail performance costs of coordinating two tasks (Bourke, 1996). In this task, the low load condition consists of a string of digits in a fixed order (i.e. “123456”), whereas the high load condition would be the exact length but in a randomized order (e.g. “462153”). Tasks which require a rehearsal process were thought to recruit the central executive component of WM (Baddeley & Hitch, 1974; Cowan, 2001). However, it is also known that the central executive controls several components which process modality specific information (Repovš & Baddeley, 2006). For instance, the phonological loop encodes verbal information, whilst the visuospatial sketchpad processes spatial relations and object features. Previous research suggests that each WM component does not exert an equal influence on visual selective attention. In a study by Baddeley (1992), a group of chess players were presented with several experimental conditions either tapping into the central executive, phonological loop and visuospatial sketchpad independently. The main task was to remember locations of chess pieces and reproduce the movements which required the visuospatial sketchpad. The results confirmed the predicted impairment of performance when the central executive or visuospatial sketchpad was suppressed relative to the phonological loop. A notable dissociation found by Morey (2018) was that visuospatial WM contents were susceptible to the concurrent maintenance or processing of verbal information, but the reverse was not true. In a recent study, Allen and colleagues (2017) conducted a series of experiments and found no consistent interaction between executive control load and visual distraction. Their experiments demonstrated that people were not necessarily more prone to perceptual distraction when executive attention was loaded despite an overall reduction in performance accuracy. Allen and colleagues (2017) acknowledged that executive control load differs from load onto specific EF as proposed by Friedman & Miyake (2004) such as updating, shifting and inhibition. These authors suggested the need to carry out studies specifically testing the aforementioned specific EF.

Load Theory of Selective Attention and Cognitive Control

It has been acknowledged that selective attention can be influenced by either top-down or bottom-up signals during visual search (Yantis, 2000; Buschman & Miller, 2007). In general, late selection theories argue that distractor interference effects occur from processing both attended and unattended stimuli, whereas early selection theories would argue that said effects were failures of attentional selection. The *Load Theory of Selective Attention and Cognitive Control* ("Load Theory": Lavie et al., 2004) sought to provide a resolution to the long-standing early-versus-late-selection debate in attentional research. Lavie and colleagues (2004) proposed that an active attentional control mechanism relied on higher cognitive functions such as WM. De Fockert and colleagues (2004) found an indirect link between attentional capture of singleton stimuli and WM through the negative correlation between the magnitude of capture and left frontal cortex activity. WM may then play a role in not just the detection of singleton(s) but also in minimizing attentional capture (De Fockert, 2013). The role of WM is to maintain prioritization of targets amongst distractors in selective attention tasks especially under conditions of dual tasking. Lavie and De

Fockert (2004) reasoned that the failure to find WM load effects on selective attention may be due to the absence of competition between high-priority targets and low-priority but salient distractor items. Under high cognitive load, there are reduced resources for WM to actively control attention so there is reduced capacity to distinguish between relevant and irrelevant targets. The impaired ability to prioritize relevant stimuli has been supported by Carmel and colleagues (2012) as well as studies which have corroborated findings for an increase in distractor processing with increasing WM load (De Fockert et al., 2001; Rissman et al., 2009; Kelley & Lavie, 2010). Top-down settings such as task instructions are necessary for relevant information to be given higher priority while suppressing irrelevant information (Lavie, 2010). Lin & Yeh (2014) considered Load Theory to be a domain-general account in that attentional control can be biased by memory load regardless of modality. Clear effects have demonstrated in favour of this dominant theory of attention regarding visual perceptual load, but WM load effects remain disputed (Murphy et al., 2016). There are studies which have not replicated increased distractor interference effects with greater WM load (Rose et al., 2005; Sreenivasan & Jha, 2007; Jongen & Jonkman, 2011).

Dilution Theory

An alternative approach to Load Theory was initially proposed by Tsal and Benoni (2010) for explaining inconsistencies in perceptual load effects. It has since been extended to all types of load due to the unclear distinction between perceptual load and WM load (Benoni & Tsal, 2013). One of the main ideas was that the Dilution account considers the status (i.e. relevance) of additional items in a display whereas Load Theory does not. Tsal and Benoni (2010) suggested that studies in support of Load Theory did not consider display size as a confounding variable. The idea of dilution was based on earlier ideas surrounding the early visual interference account (Brown et al., 1995). Dilution is thought to occur at the early stage of visual processing, and distractors are processed in a parallel rather than serial manner (Kahneman & Chajcyzk, 1983; Yee & Hunt, 1991). In several studies, the Dilution effect has been replicated (Benoni & Tsal, 2010; 2012) and some results have indicated that all types of load (albeit perceptual or cognitive) increased distractor interference (Benoni et al., 2014). Wilson and colleagues (2011) extended the Dilution hypothesis to include a two-stage process of visual search. When one item reaches the focused attention stage, all other items become irrelevant. It is predicted that the dilution effect increases as a function of set-size, hence decreasing distractor interference (Wilson et al., 2011).

Specialised Load Theory

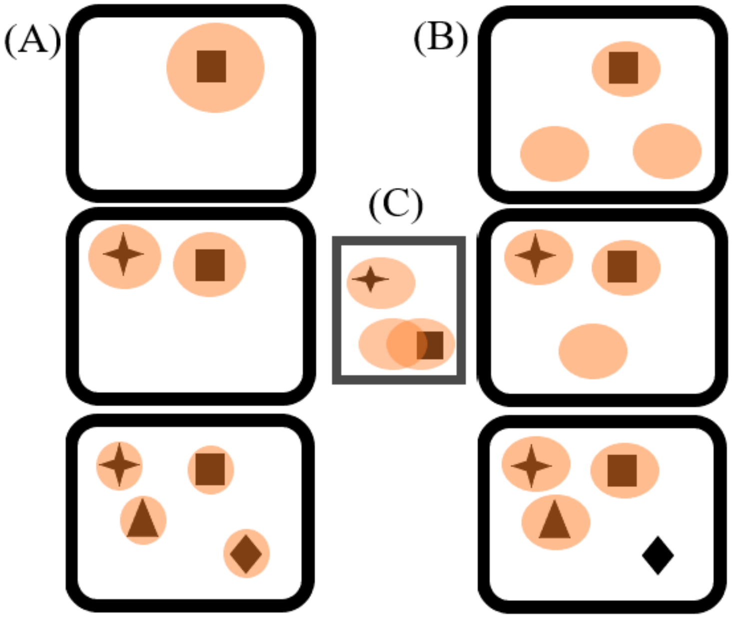
In the *Specialised Load Theory,* Park and colleagues (2007) postulate that the effect of WM load is modality-specific. For example, in their dual-task condition, participants' task performance was impaired when the content held in their WM overlapped with the target category. They were worse at making same/different judgements between pairs of faces whilst maintaining faces in WM, and this was attributed to resource competition. On the other hand, in cases where faces were categorized as to-be-ignored (distractor), performance was facilitated for same/different judgements of other information (i.e. houses) with faces maintained in WM. The authors explained that efficient target selection was caused by load depletion in resources allocated for distractor processing. This theory was preceded by modality specific effects demonstrated by researchers investigating with the assumption that multiple and independent pools of resources exist (Kim et al., 2005). Multiple discrete pools of resources underpin the effect where tasks which share the same limited resource would yield interference with each other, but this logic would not apply across modalities. Kim and colleagues (2005) posited that even improvements in target selection could occur if the WM load content exhausted the resources allocated for distractor processing. Domain-specific ideas are compatible with Baddeley's model of WM (Baddeley, 2003) which makes a distinction between processing of verbal and visuospatial information whereby the greatest interference occurs in verbal-verbal tasks versus visual-verbal tasks. Another study in favour of modality-specific effects found that visual WM had slightly more influence than other WM components such as spatial WM, verbal WM and executive load on selective attention (Burnham et al., 2014). The authors interpreted their findings in terms of adding to revisions that can be made to the Load Theory framework. When both the primary and secondary task required the same WM component, the secondary task exerted more interference with regards to distractor rejection. This finding is consistent with that of Lin and Yeh (2014), who demonstrated that the influence of increased distractor interference was much greater than its reduction.

2.1.2 Visual Working Memory Capacity

VWM has been conceptualised as the short-term “on-line” storage of information in which visual information is quickly accessible and malleable (Luck, 2008). Previous research has established that VWM is severely limited in capacity (Luck & Vogel, 2013; Ma et al., 2014). Liesefeld and colleagues (2020) have posited that filtering is implemented within VWM by keeping irrelevant information out of WM (i.e., distractor suppression). With reference to the biased competition model (Desimone & Duncan, 1995), it is assumed that salient stimuli will compete for access to VWM. The visual system is not limited to biases from bottom-up factors but can also be influenced by top-down modulation. Models of visual attention are in agreement that certain locations in space are prioritized for upcoming behaviour or cognitive processes. However, not every salient piece of information is relevant, and some models have included an aspect of relevance overriding this attentional bias (Folk et al., 1992, Yantis & Johnson, 1990). A priority map can encompass the transition from visual salience to relevance-driven processing (Zelinsky & Bisley, 2015; Sprague et al., 2017). The study of VWM has focused on the capacity aspect of the system because limited capacity is regarded as a hallmark of WM. There are two dominant models in the study of VWM capacity; the discrete slots theory (Luck & Vogel, 1997; Vogel & Machizawa, 2004) and the continuous resources theory (Bays & Husain, 2008). According to the former, VWM capacity has a limited number of slots to be allocated, i.e. one item per slot. Recent revisions to the model posit that an item can be represented by multiple slots if the maximum number has not been exceeded (Zhang & Luck, 2008). As seen in Figure 2.1, it should be noted that the level of precision differs between the models at each set-size. For two items, the additive slots model would predict that precision is greater for the item which is stored in two slots than if it was held in a single slot. A discrete slot-based theory would assume an equal amount of resources was allocated to each item, hence the precision of recall for each remembered item should be equivalent. The slot-based memories work to the all-or-none principle in that items falling outside the maximum amount of slots will not be remembered at all. In contrast, resource theories of VWM capacity assume that there is a flexible division of resources (Bays & Husain, 2008) without a limit to the number of items which can be stored. The assumption is that precision would be higher for the two-item condition as compared with a four-item condition. Both models have received support from empirical studies (Barton et al., 2009; Rouder et al., 2008; Zhang & Luck, 2011; Bays et al., 2011). The general consensus is that VWM has an extremely limited capacity and that 1 item can be represented with greater fidelity than 3–4 items (Brady et al., 2011).

***Figure* 2.1**

Allocation of resources according to VWM capacity models (adapted from Machizawa, 2012).



Note. The amount of resources allocated for each item is represented by the orange circles. Based on a 3-item capacity limit, panel (A) represents the *continuous resource* model, and panel (B) illustrates the *discrete slots* model prediction for set-size 1, 2 and 4. Panel (C) illustrates the *additive slots* assumption.

Visual Working Memory Capacity Effects in Selective Attention

Alongside the developments in the domain of VWM capacity, there has been research in the link between VWM capacity and central executive resources within the context of distractor suppression (Hester & Garavan, 2005). Measures of WM capacity have been thought to reflect an individual's ability to maintain information in highly accessible state and control attention amidst interference (Engle, 2002; Kane & Engle, 2003). A correlation has been found between a person's WM capacity and ability to inhibit prepotent responses as indexed by interference tasks (e.g. Stroop task). Kane and colleagues (2001) demonstrated that low-span participants had higher interference scores than the high-span group after controlling for between-group differences. A key finding was that participants with a WM span were able to better suppress irrelevant information or responses, and not because of they possessed more capacity to store information. A study by Ahmed and De Fockert (2012a; 2012b) sought to examine the combined effects of high and low WM load and WMC on selective attention. The automated Operation span task developed by Unsworth and colleagues (2005) was administered to investigate the individual differences in WMC. The key prediction made by the authors was that if the propensity to distraction is modulated by the availability of resources, then people would be more likely to be distracted when WM resources were increasingly exhausted. More specifically, the high WMC group under low WM load would demonstrate the best level of performance in a Stroop task. The results fully supported this prediction, but there was also an unanticipated finding in that the low WMC group showed a reduction in the congruency effect with increasing WM load. The conclusion drawn from this study was that WM limitations affected the spatial profile of attention rather than the extent of distractor processing. Thus, high WMC individuals were more able to adjust their attentional window to task-relevant information. However, the authors note that this pattern of findings may not apply to situations in which distracting information is not spatially distinct from a relevant target (Stroop, 1935) or when targets and distractors are presented in succession (Gazzaley et al., 2005). In a series of experiments by Yao and colleagues (2020), the role of VWM capacity was examined from three different perspectives: Load Theory hypothesis (VWM capacity as perceptual load), resolution hypothesis (VWM capacity as central executive load) and domain-specific resolution hypothesis. The overarching results from a meta-analysis of twelve experiments, indicated that VWM load did not modulate distractor processing, with the effect size of the VWM capacity load being low and the Bayes Factor value in favour of the null hypothesis (Yao et al., 2020). In one of the experiments, Lin and Yeh's (2014) findings were replicated in that VWM load using non-verbalized shapes increased the flanker effect but the authors found that the result was contaminated by the unbalanced spatial distribution of the memory array. The failure to replicate previous results could go beyond discrepancies in parameters such that there may be a moderator variable modulating the link between VWM capacity load and distractor processing. One possibility would be the differential effects of VWM resolution load (i.e., the precision of representations) versus VWM capacity load (Zhang & Luck, 2015). Although existing research recognizes the critical role played by VWM capacity in selective attention, the direction of effects remains elusive.

2.1.3 Study Aims

A primary aim of the current study was to investigate WM load effects by testing the predictions from Load Theory (Lavie et al., 2004) whilst controlling for perceptual load. However, alternative theories such as the Specialized Load theory (Park et al., 2007) and Dilution Theory (Tsal & Benoni, 2010) have been put forward with the existing data specific to WM load effects also warranting further investigation. It is difficult to predict the outcome a priori due to predictions in opposing directions, thus the current study may reveal the theory which better accounts for the distractor interference effects. There were several possible outcomes for the distractor interference effects under high WM load. Firstly, there could be an increased distractor interference effect as seen in studies in support of Load Theory (Lavie et al., 2004; Konstantinou & Lavie, 2013). In particular, Load Theory postulates that increased WM load depletes the resources required for the prioritization of target processing. Secondly, Dilution Theory predicts increased distractor interference for all types of loads (Benoni et al., 2014) whereas dilution will decrease distractor interference. Tsal & Benoni (2010) defined dilution as the effect from neutral stimuli, which are perceptually similar to those of the distractor, being misattributed as perceptual load. The crucial difference between Load Theory and Dilution Theory is that the latter account suggests that the relevance of the additional items does not matter. Another possible outcome would be reduced distractor interference effect, especially if the WM item shares limited capacity processing with distractors (Kim et al., 2005; Park et al., 2007). Park and colleagues predict differing distractor interference effects depending on the overlap between WM content with processing of the target/distractor stimulus. The distractor interference effect will be attenuated if the WM item shares limited-capacity processing with distractors (i.e., the experimental condition where the WM item was congruent with the subsequent distractor item).

These aforementioned studies have employed dual-task conditions (two concurrent tasks) and these settings may have inflated demands on attentional control, presumably loading onto the switching EF (Lavie, 2010). The current study differed from previous literature in several ways. WM load was operationalized in terms of loading the *updating* EF and examining its effects on the *inhibition* EF of distracting stimuli according to Miyake and Friedman's EF model (2017). This definition provides the specificity that was lacking from Load Theory's terminology (Lavie, 1995). Another way of framing the link between attention and executive control, as seen in Luck & Gold (2008), was that "executive control" load may be more likely engaging the inhibition EF (i.e. overriding prepotent stimulus-response pairings). The WM task of choice was not a digit probe task which mainly tapped into the central executive component of WM (Allen et al., 2014) rather than a specialized EF such as updating, shifting or inhibition. Instead, participants would retain a search template in WM which varied from one to four items during a retention interval which required an updating process on every trial. The four-item condition aims to strain the updating EF process more than the one-item condition. Additionally, others have found diminished effects of WM on attentional guidance when WM load reaches WM capacity of 3-4 items (Zhang et al., 2011).

The novel DMTS task enables the examination of WM load effects on the interplay between the updating EF and inhibition EF within a single task. A single task setting reduces the involvement of the shifting EF. Perceptual load was kept to a minimum with an "efficient search" task in which a single stimulus would pop-out amidst an array of homogeneous shapes/colours (similar to Fuggetta & Duke, 2017). The assumption was that perceptual load was equivalent for the distractor and target array. The current experiment extended Fuggetta and Duke's (2017) paradigm with the inclusion of a pop-out distractor singleton array which always preceded the pop-out singleton target array. The effects of an irrelevant salient singleton were so potent that even extended practice, anticipated knowledge or unconscious intention could not prevent this (Theeuwes, 1991; Weingarten et al., 2016). Behavioural responses would be slower and less accurate when a salient pop-out stimulus mismatched the initial target template in WM. This is because comparison of memory representations was more effortful in mismatch trials compared to match trials (Fuggetta et al., 2015). The prediction from Load Theory was that distractor interference would be enhanced with any type of increased WM load. The prediction from Park and colleagues (2007) was an attenuation of distractor interference under conditions where the concurrent contents of WM overlap with the distractor within the same domain. With Dilution Theory, it would be expected that additional stimuli held in memory (i.e. high WM load condition) may dilute the representation of the distractor, leading to reduced distractor interference.

2.2 Method

2.2.1. Participants

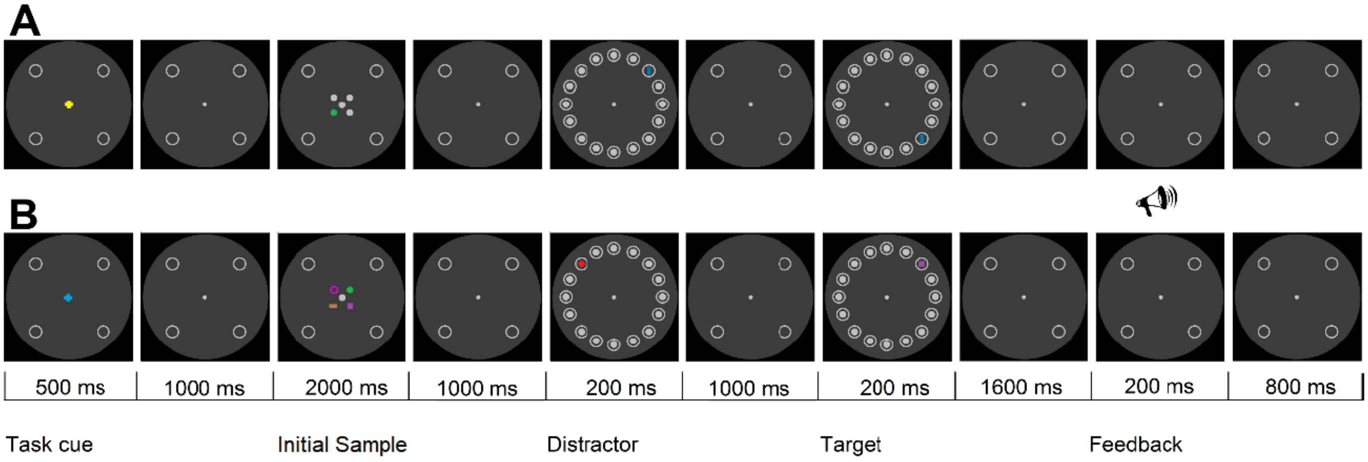
The sample size (*N*=23) for Experiment 1 was a priori calculated using G*power 3.1. (Faul et al., 2007) for the repeated measures ANOVA, with an expected medium effect size (η2 = 0.06), power of .80, and alpha level of .05. 27 volunteers started the experiment and provided written informed consent but 24 were included in the data analysis. 1 participant was excluded due to the age criterion of 18-40 years and 2 had failed to complete the behavioural task (M age = 19.67 years, range = 18-24 years, SD = 1.31, 18 females, 4 left-handed). All participants had normal or corrected-to-normal vision and reported no use of medication, history of psychiatric or neurological disorders. Participants were students recruited from the University of Roehampton’s Psychology department and participation was awarded with course credit. Full debriefing about the purpose of the study was given to participants at the end of the experiment. Ethical approval was granted by the ethics committee of University of Roehampton.

2.2.2 Materials and Procedure

Visual task A delayed match-to-sample (DMTS) task combined with an efficient visual search (Fuggetta & Duke, 2017; Barras & Kerzel, 2017) where pop-out for identity and spatial position was the source of distractor interference effect. There were two tasks: colour or shape. The participants judged whether the target matched or mismatched the informative cue(s) shape or color (i.e. match-to-sample task), irrespective of spatial position via the left or right button responses of a mouse (Figure 2.2). The irrelevant distractor was either matching the incoming target (congruent condition) or mismatching the target (incongruent condition). Participants were given explicit instructions to always ignore the distractor array. Therefore, the display items are labelled as follows: initial WM item (S1), the distractor array (S2) and the target array (S3). Distractor interference effects on performance indicated the extent to which the salient irrelevant singleton induced compatibility effects on a subsequent target array (Kristjánsson & Campana, 2010). The distractor position did not predict the location of the target stimuli.

Figure 2.2

Example of sequence of events of two trials of the pilot study varying the *updating* EF load.



Note. (A) This trial is an example of the shape task, low WM load and incongruent condition. This task cue is a yellow fixation cross, the initial sample contains one shape to be rehearsed in WM and the distractor is different from the target shape. (B) This trial is an example of the colour task, high WM load and congruent condition. The task cue is a blue fixation cross, the initial sample consists of four shapes to be rehearsed in WM and the distractor is similar to the target colour. Please note that the task was kept constant within blocks of trials. For illustrative purposes, the auditory feedback in the experiment is represented by a horn speaker icon.

Participants completed 512 trials in eight blocks of 64 trials and were allowed to pause between blocks. Informative cue shapes, distractor position, target position shapes, task and their combinations were randomized within blocks. However, the response mapping (i.e. press the left mouse button for target different from the informative cue and right mouse button for target matching the informative cue or vice versa) was counterbalanced across participants. Participants were naïve to the aims of the experiment. All participants were tested individually in a dimly lit room and completed the experimental task for approximately 1 hour. To reduce head motion, a chinrest was used for each participant with a fixed viewing distance of 71 cm. Participants completed 32 practice trials to familiarize themselves with the task before the main experimental phase. The practice phase was repeated until the participant understood the task but no more than

3 times. Participants were instructed to fixate on the screen throughout trials. They were told to respond as quickly and accurately as possible using a mouse. Behavioral performance (response times and performance accuracy) was recorded. An in-house experiment generator software programmed with Lazarus (https://www.lazarus-ide.org/) was used to present the experiment on a 24" LCD monitor (AOC G2460PG G-SYNC) with 1 ms response time, a resolution of 1920 x 1080 pixels and a refresh rate of 100 Hz.

Sequence of Events The monitor continuously displayed a 0.3^o white fixation spot (32.50 cd/m^2) in the centre of a 17.4^o grey circle (10.06 cd/m^2), against a black background. Four empty white rings (i.e. placeholders, 32.50 cd/m^2) with an outer diameter of 1.6^o and inner diameter of 1.4^o (0.1^o thickness) were presented in the top-left, top-right, bottom-left and bottom-right quadrants around the circumference of an imaginary 5.5^o radius circle around the central fixation point. This restricted visual search to the four positions required to perform the shape/colour discrimination task. The visual task comprised of the following stimuli: First, a foveally presented task cue, either a bright yellow or cyan (96.48 cd/m^2) “+”, at the beginning of each trial, was presented for 500 ms and cued which task (shape or colour match-to-sample task) to perform during an entire block of trials.

Secondly, an informative cue array was shown for 2000 ms and comprised of five shapes: a 1.3^o white (32.50 cd/m^2) circle always presented at the centre of the screen and four shapes presented in the top-left, top-right, bottom-left and bottom-right quadrants surrounding the circumference of an imaginary 2^o radius circle. These four shapes could be either three 1.1^o white circles and one colored different shape (i.e. low WM load condition) or four colored heterogeneous shapes (i.e. high WM load condition). The shapes used as informative cues were: 1.5^o x 1.5^o diamond, 1.2^o x 1^o hexagon, 1.3^o x 1.6^o triangle, star, 1.3^o ring, 0.8^o x 1.6^o horizontal bar, 1.6^o x

0.8° vertical bar and 1.2° x 1.2° square. The colors used as informative cues were isoluminant (32.20 cd/m^2): red, green, cyan, yellow, magenta, brown, blue and purple. The RGB values can be found in Appendix F(i). Thirdly, a task-irrelevant distractor array was shown for 200ms. All of the shapes and colors used as informative cues were also shown as a distractor (S2). The distractor appeared within one of the four placeholders among fifteen non-target homogeneous distractors as 1.3° diameter white circles and spaced evenly on the circumference of an imaginary 5.5° radius circle around the central fixation point.

Additionally, a target array with a target shape or color (depending on the current block of trials) embedded amongst fifteen non-target homogeneous distractors was shown for 200ms. The characteristics and duration of the target array were identical of those of the distractor array. A 200ms-long segment of auditory feedback was presented towards the end of a trial, i.e. high pitch tone for correct responses and low pitch for incorrect or no response. The task cue, informative cue, distractor, target and feedback were followed by fixation and four placeholders' screens having durations for 1000, 1600 and of 800 ms, respectively (see Figure 2.2).

2.2.3 Experimental Design

The independent variables were WM load which consisted of four conditions (i.e. set-size one, two, three or four to rehearse in WM) and distractor type (mismatching the initial sample, matching the initial sample). The dependent variables were reaction times (milliseconds) and error rates (as a percentage). The magnitude of distractor interference effect of the initial sample on the distractor (S2) was computed by subtracting the task performance between the following two conditions: Distractor Type Mismatching minus Distractor Type Matching. It was a blocked design as to minimize any involvement of the shifting function i.e., pure blocks of shape/colour task. To control for perceptual load, only a single item appeared as a distractor and as a target amongst homogeneous white circles in the visual search array. Additionally, the Cowan’s K capacity estimates were calculated for each participant as a complementary measure i.e., the number of correctly remembered items for each set-size condition.

2.3 Results

In all ANOVAs, Greenhouse-Geisser epsilon adjustments were applied for cases of non-sphericity. As for post-hoc paired t-tests, multiple comparisons were Bonferroni corrected. A two-tailed hypothesis was used therefore ($\alpha = .05$). All statistical analyses were performed using Statistical Package for the Social Sciences Statistics (SPSS Version 26, IBM).

Only correct responses and responses less than 1800 ms were logged by the system with 4.2% of trials removed from analysis. RTs (milliseconds) and percentage error rates of correct responses were analyzed with a 2 x 4 repeated measures analysis of variance (ANOVA). The within-subjects factors were WM load set-size (1, 2, 3, 4 items) and Distractor Type (mismatching the initial sample, matching the initial sample). Mean RTs and error rate values can be found in Table 2.1. The analysis was combined rather than splitting the variables by task (i.e., colour and shape).

Table 2.1
Mean RTs (milliseconds) and Mean Error Rates (%) by WM Load and Distractor Type.

RTs/ Error Rates	Distractor_Matching	Distractor_Mismatching
WM Load 1	653.57 (158.98)	696.72 (153.94)
WM Load 2	711.91 (148.23)	751.37 (155.62)
WM Load 3	766.34 (169.63)	794.38 (154.81)
WM Load 4	782.46 (161.43)	809.60 (167.48)
WM Load 1	8.39 (12.32)	10.82 (10.40)
WM Load 2	12.17 (13.06)	15.48 (12.45)
WM Load 3	14.91 (13.07)	23.59 (12.56)
WM Load 4	20.45 (12.38)	25.94 (13.58)

Note: Standard Deviation values are shown in parentheses.

2.3.1 Reaction Times

ANOVA of RTs revealed a significant main effect of WM load *F*(2.04, 46.89) =59.45, *p*<.001, ηp2 =.72 showing that participants were slowest in response to WM load set-size 4 (*M*=796.03, *SE*=33.08), set-size 3 (*M*=780.36, *SE*=32.57), set-size 2 (*M*=731.64, *SE*=30.35) and then set-size 1 condition (*M*=675.14, *SE*=31.37). Pairwise comparisons (Figure 2.3) showed that RTs were significantly different across conditions (*ps*<.001) apart from set-size 3 versus set-size 4 (*p* = .35). There was a significant main effect of Distractor Type *F*(1, 23) =23.00, *p*<.001, ηp2 =.50 revealing that participants were slower to respond to distractors mismatching (*M*=763.07, *SE*=31.12) than distractors matching (*M*=728.57, SE=31.83) the initial sample (Figure 2.4). There was no significant two-way interaction between WM load set-size and Distractor Type *F*(3, 69)= .51, *p*=.68.

Figure 2.3

Main effect of WM Load set-size on RTs.

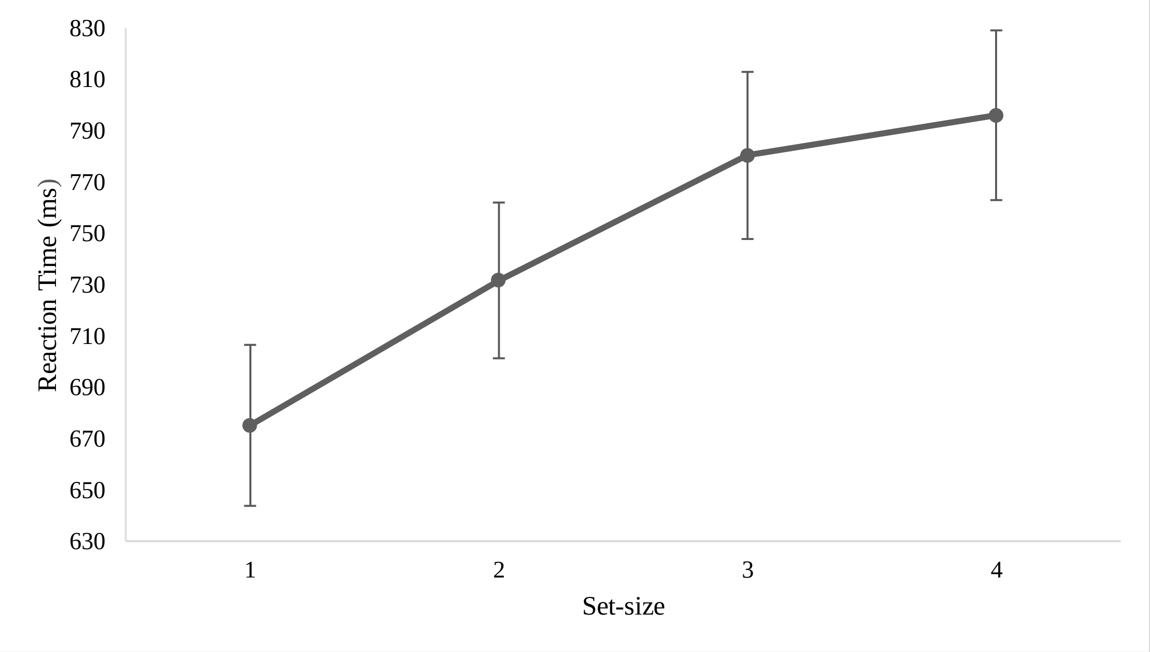
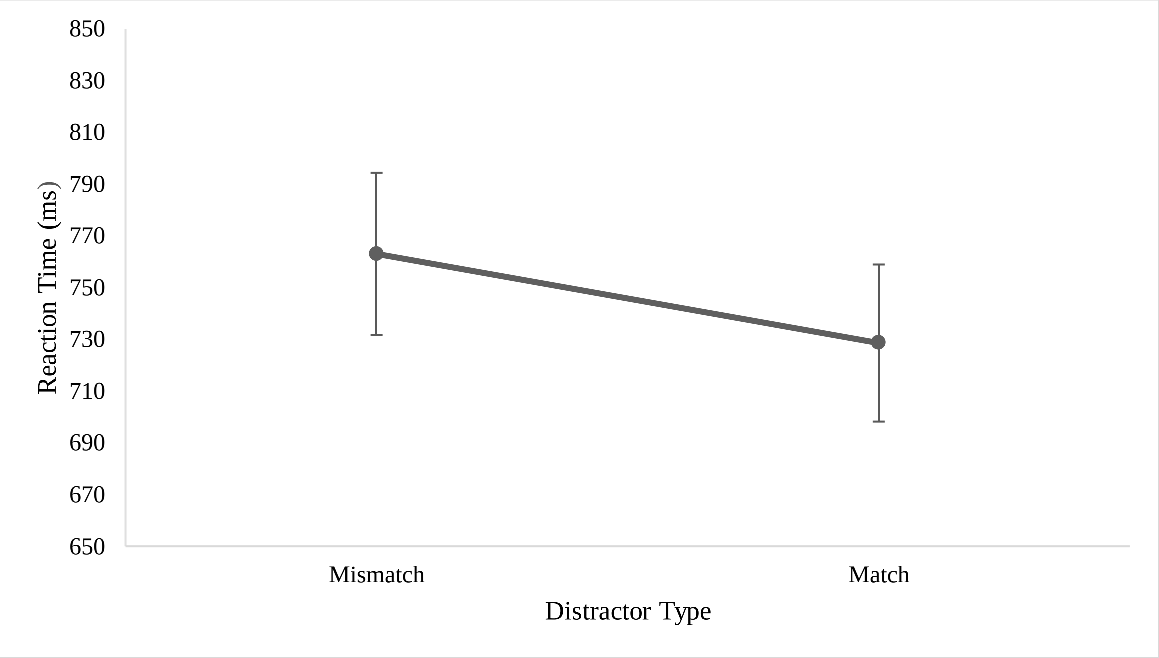


Figure 2.4

Main effect of Distractor Type on RTs.



2.3.2 Error Rates

ANOVA of error rates revealed a significant main effect of WM load *F*(2.19, 50.37) =65.98, *p*<.001, ηp2 =.74 showing that participants were least accurate in responding with WM load set-size 4 (*M*=23.2, SE=2.5), set-size 3 (*M*=19.3, SE=2.5), set-size 2 (*M*=13.8, SE=2.5) and then set-size 1 (*M*=9.6, SE=2.2). Post-hoc comparisons (Figure 2.5) showed that error rates were significantly different across all conditions (*ps*<.001). There was a significant main effect of Distractor Type *F*(1, 23) =41.20, *p*<.001, ηp2 =.64 revealing that participants were less accurate at responding to distractors which mismatched (*M*=19, SE=2.3) than distractors which matched (*M*=14, SE=2.5) the initial sample (Figure 2.6). The two-way interaction between WM Load x Distractor Type was significant *F*(3, 69) =4.07, *p*=.01, ηp2 =.15. Post-hoc comparisons for the WM Load x Distractor Type interaction (Figure 2.7) revealed that error rates did not significantly differ between matching and mismatching distractors within set-size 1 (*MD*= 2.4, *SE*=1.4) whereas other comparisons were significant *ps*<.001. The largest compatibility effect was between matching and mismatching distractors within set-size 3.

Figure 2.5

Main effect of WM Load set-size on Error Rates.

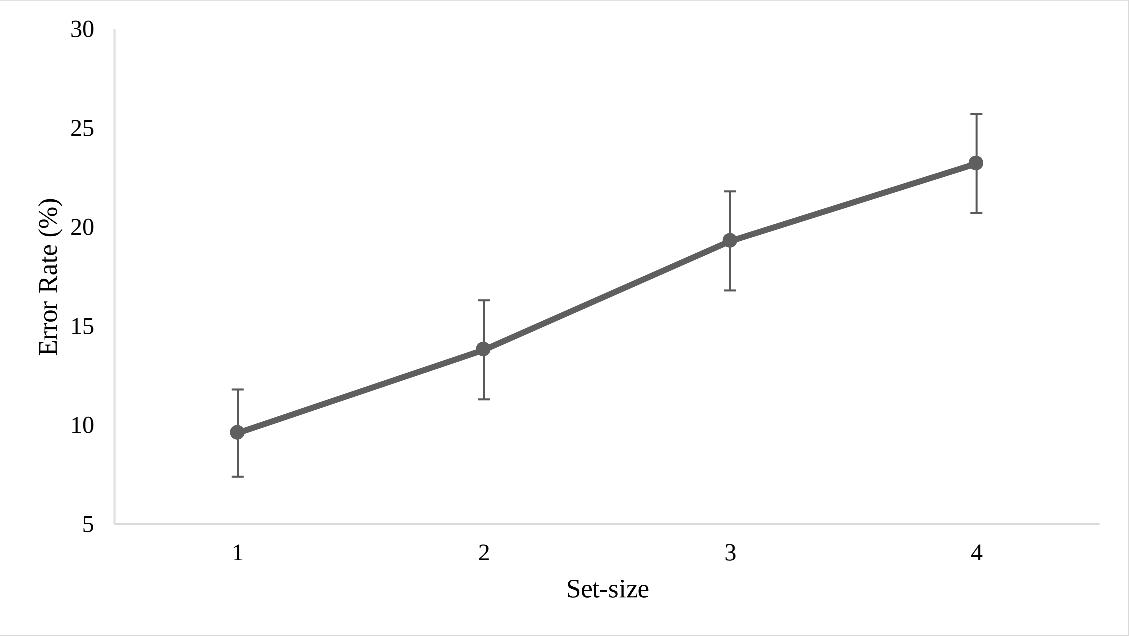


Figure 2.6

Main effect of Distractor Type on Error Rates.

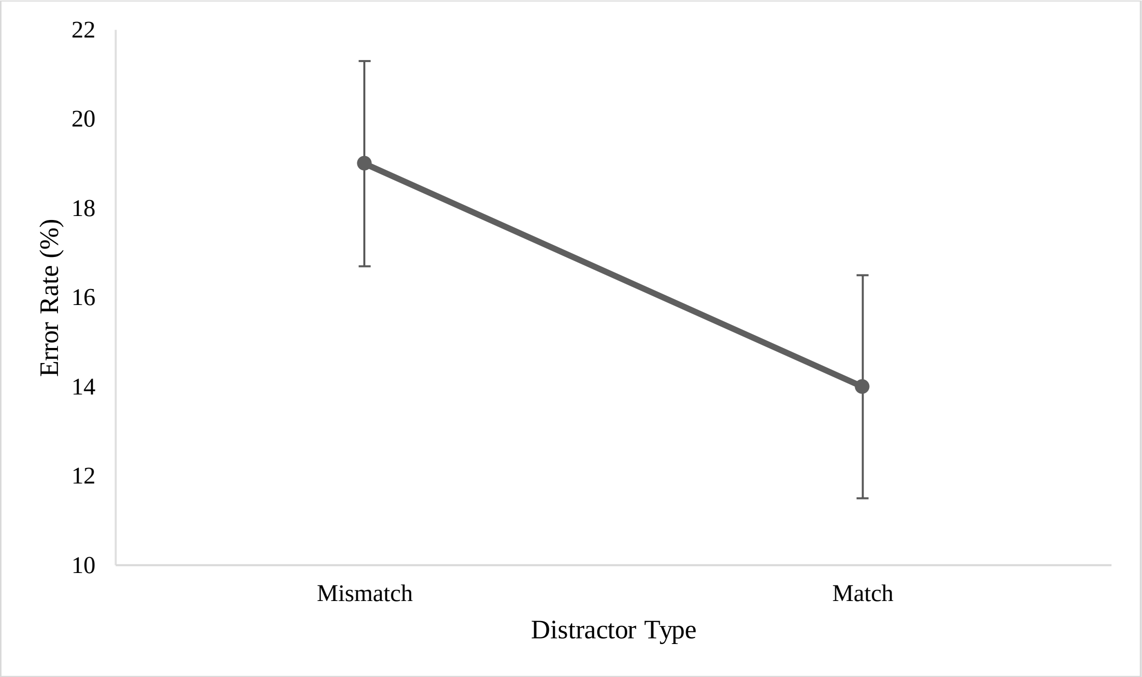
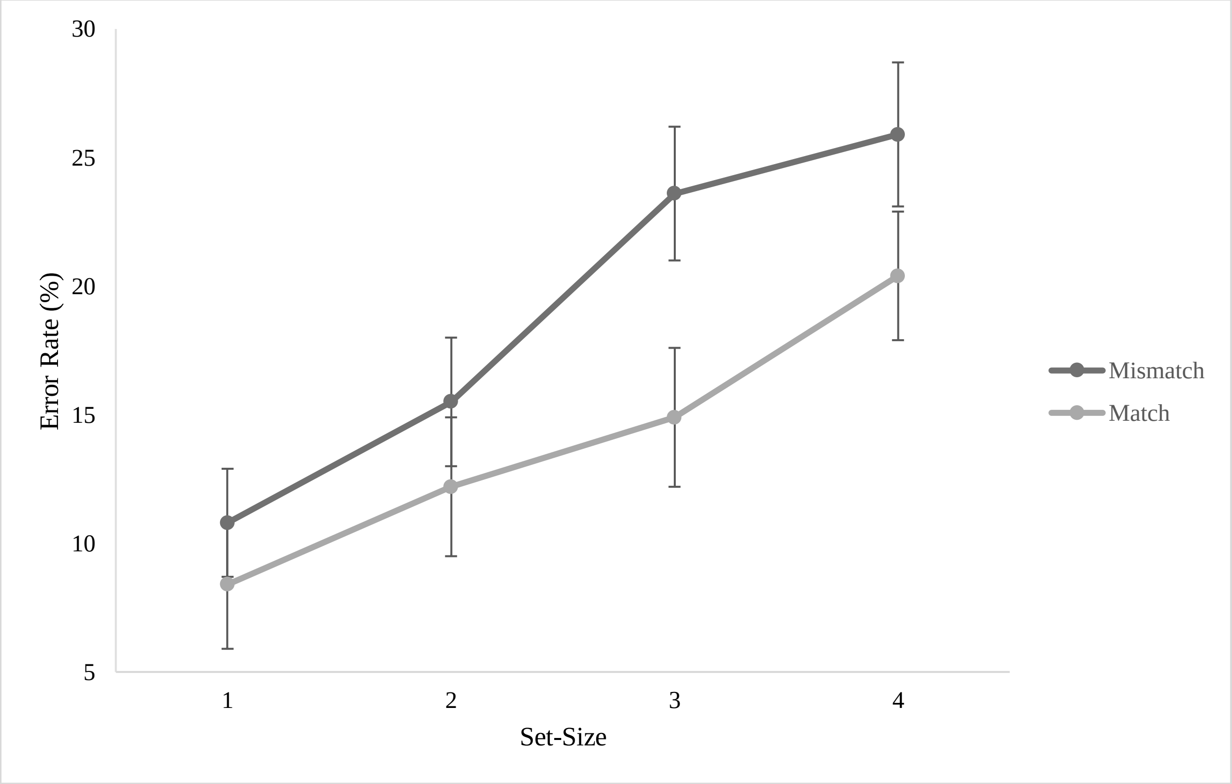


Figure 2.7

The WM Load Set-Size x Distractor Type Interaction for Mean Error Rates.

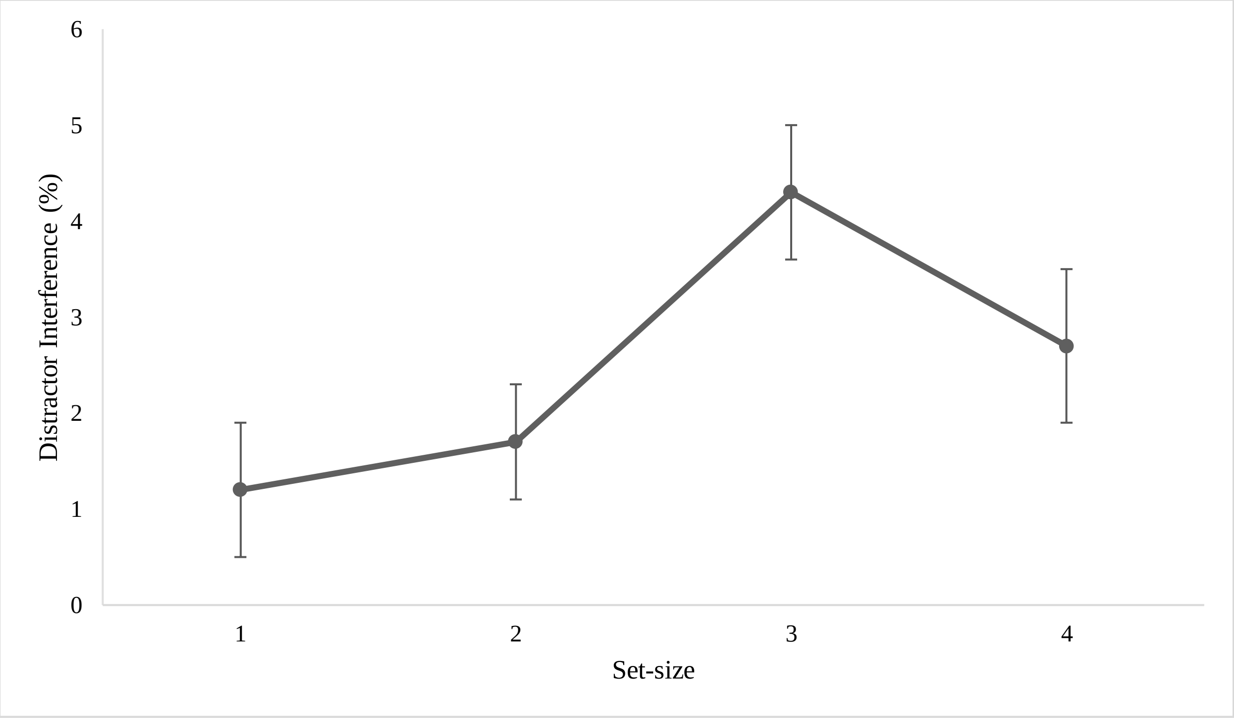


2.3.3 Distractor Interference Effect

The magnitude of distractor interference effect of RTs and error rates were computed as the difference in compatibility between conditions: Distractor Type Mismatching minus Distractor Type Matching (similar to Kelley & Lavie, 2010). A follow-up repeated measures ANOVA with WM load (set-size 1, 2, 3 and 4) as a single within-subjects factor was conducted. The ANOVA results for RTs demonstrated no significant distractor interference effects *F*(3, 69) =.51, *p*=.68. The main effect of WM load for error rates was significant *F*(3, 69) =4.07, *p*=.01, ηp2 =.15. Pairwise comparisons revealed that the distractor congruency effect was significantly different between WM load set-size 1 and 3 (*MD*= 3.1, *SE*= 1.0, *p*= .02) as well as WM load set-size 2 and 3 (*MD*= 2.7, *SE*= .08, *p*= .01). All other comparisons were not significant (*ps*>.05).

Figure 2.8

Distractor Interference Effect for Mean Error Rates.



2.4 Discussion

The current study investigated the effects of varying WM updating load set-size on the ability to inhibit distractor processing in a single-task setting. The advantage of a single-task paradigm is that it reduces the influence of the shifting EF (Miyake et al., 2000) and additional demands placed on cognitive control where dual-task coordination is required. In extreme cases, having to coordinate two tasks puts a strain on visual attentional control processes, regardless of WM memory load or the extent to which they overlap (Olivers et al., 2006). There were several possible outcomes for the modulation of WM load on inhibitory processing of salient peripheral distractors. There could be a depletion of attentional control whereby high WM load would disrupt the active maintenance of stimulus processing priorities leading to increased processing of distractors (Lavie et al., 1994). Another outcome would be a domain-specific effect, i.e. a decrease in the processing of distractors for distractor-related WM load as compared to target-related WM load under the assumption that these items shared the same pool of attentional resources (Kim et al., 2005). Tsal and Benoni (2010) predict that distractor interference can be reduced with the addition of items in a display which dilute the representation of the distractor. Overall, there was partial support for predictions from Load Theory (Lavie et al., 2004) even with the use of a novel experimental task.

Firstly, the significant interaction between updating WM load and distractor-initial sample compatibility for percentage error rates was significant for set-size 2 and upwards. This pattern of findings support Load Theory as there is increased compatibility effects for set-sizes 2 to 4. Whilst the seminal paper on Load Theory (Lavie et al., 1994) has not provided thorough explanations for WM capacity related effects, the greatest compatibility effects found in the WL load set-size 3 condition but a slight reduction of effects at set-size 4 can be explained by approaching its maximal capacity (Cowan, 2001; Luck & Vogel, 1997). Alternatively, the biased-competition model

(Desimone & Duncan, 1995) could account for the absence of attentional guidance effects from WM content. This account emphasizes the role of feedback from the prefrontal cortex to more temporal regions in enhancing a visual representation. If the WM load was too high, there were insufficient resources to complete this feedback loop for successful maintenance leading to more errors. The presence of compatibility effects suggests that the top-down bias toward the target colour/shape singleton could not prevent attentional capture by a distractor colour/shape singleton (Theeuwes & Van de Burg, 2011) despite explicit instruction to ignore the distractor array. The retrieval of information may have degraded since the initial memory sample array was encoded. A relatively long interval of 3,500ms was used between the initial sample and target array onset which could have potentially inflated memory degradation (Todd & Marois, 2004).

Secondly, the magnitude of compatibility effect calculated for error rates was significant and did support the predictions from Load Theory. In the error rate data, the distractor interference effect was only significantly different between WM load set-size 1 and 3 as well as set-size 2 and 3. Predictions from WMC theories in favour of discrete slots (Luck & Vogel, 1997; Zhang & Luck, 2008) state that a comparable level of accuracy should be maintained until the capacity limit is exceeded i.e., WM load set-size 3 in the current study. These results partially supported Specialised Load theory (Kim et al., 2005) as distractors which matched the WM item competed for limited resources leading to less distractor interference than the mismatching condition. If there was a domain-general pool of attentional resources, there would be no difference between the types of distractors. From the view of Dilution theory, the additional stimuli held in memory may dilute the representation of the distractor. Given that the distractor array controlled for perceptual load (i.e. similar set-size display to target array), dilution occurred in the high load WM item arrays. The tentative conclusion is that executive demands were at maximal in set-size 3 but there was interplay with dilution at set-size 4. The idea of an interplay was also discussed by De Fockert

(2013) that the to-be-attended feature and to-be-ignored feature, within the same domain, would counteract each other.

Thirdly, the main effect of WM load for both RTs and error rates confirmed that the load manipulation was successful. There was no evidence for a speed–accuracy trade-off, as an increase in RTs was accompanied by higher error rates. There was no significant interaction between updating WM load and distractor type for RTs. As for the RT distractor interference effect, this was not significant either but showed a trend in reduced interference similar to previous studies (Kim et al., 2005; Park et al. 2007) and was in direct opposition to Load Theory (Lavie et al., 2004). The Cowan's K value (refer to Appendix H) observed with increased WM load set-size reaches 2 items (similar to Roper & Vecera, 2014; Xu et al., 2018) which is slightly lower than those reporting 3-4 items. It should be noted that Cowan's K is the difference in capacity between conditions within participants rather than an absolute estimate of capacity limits.

The current study has served as a starting point in terms of synthesising the theories of WM and attention. For instance, the spotlight of attention analogy proposed by Luck and Gold (2008) is coherent with the focus of attention concept by Cowan (2001) and also the two-stage account of visual search (second stage of focused attention) in relation to Dilution Theory (Wilson et al., 2011). At a behavioural level, with a single task paradigm, it has been demonstrated that both Load Theory and Dilution Theory is at play within the context of distractor interference effects. When WM is not as heavily burdened (set-size 1), there appears to be no effect of distractor relevance which can be explained either by a) sufficient capacity for processing both WM item and distractor or b) the single item reaching a focused attention stage for processing. When WM is moderately burdened (set-size 2 to 3), Load Theory (Lavie, 2010) can explain the increased distractor interference effects via disruption to prioritisation process of relevant versus irrelevant items. In contrast, if WM is completely taxed (set-size 4), there are other influences such as dilution which can explain a slight reduction in the magnitude of distractor interference. Dilution Theory emphasised that the relevance of additional items mattered and all the WM items were relevant for task performance therefore additional items would have diluted the representation of the distractor (Tsal & Benoni, 2010; Wilson et al., 2011). Alternatively, WMC theories would attribute weakened effects of WM items on attention as it approaches capacity limit (Zhang et al., 2011).

With regards to the operationalization of load, the conception of the experimental design was driven by the multicomponent model of WM (Baddeley & Hitch, 1974; Baddeley, 2003) beyond the domain-general load on the central executive. The shapes and colours chosen for the experiment were initially intended to target the visuo-spatial sketchpad. In hindsight, the shapes and colours were not purely visual and were considered familiar thus were inherently linked to a verbal tag e.g. “circle”. Therefore, future experiments should control for this by incorporating a set of ‘pure’ non-verbal stimuli: abstract or nonsense shapes relying exclusively on VWM (Attneave & Arnoult, 1956; Lin & Yeh, 2014). Given that 1,200ms was the optimal delay to maximise VSTM capacity, it is also suggested that other rehearsal strategies may have been used (Todd & Marois, 2004). Other researchers may want to consider the cognitive strategy used by individuals whether they rely on verbal or visual rehearsal (Blazhenkova & Kozhevnikov, 2009). Accounting for strategy would resolve the limitation of the current study that the phonological loop was possibly engaged in WM and increased the possibility of distractor interference. Furthermore, the present study had a longer encoding time of 2,000ms as compared to 200ms (Zhang & Luck, 2015) which cannot exclude the possibility that participants created a verbal code for each item. It is plausible that significant differences in error rates from WM load set-size 2 and upwards are equivalent to performance for 2 items with articulatory suppression as observed in Soto and Humphrey (2008). As it stands, there isn’t sufficient evidence to support Specialised

Load theory as it is not guaranteed that participants encoded WM items and distractors in the same modality as initially presumed (Park et al., 2007).

A possible avenue for future investigations would be to correlate measures of WMC such as complex span tasks and task performance to see whether individual differences in WMC can modulate effects of selective attention (Redick et al., 2012; Shipstead et al., 2012). A complex span task requires a person to remember items, whilst being interrupted by another processing task. Additionally, WMC capacity may be different for real-world objects in contrast to simple colours (Brady et al., 2016). An alternative theoretical framework to consider is the neurocognitive task-engagement/distraction trade-off theory (Sörqvist & Rönnberg, 2014) which examined the role of individual differences in the ability to control attention and "shield" against task-irrelevant information. Previous studies have investigated other mediating factors of attentional control such as schizotypy (Fuggetta et al., 2015), anxiety (Eysenck et al., 2007), aversive distractors (Stout et al., 2020), attentional zoom (Lee & Jeong, 2020), statistical exposure-based learning (Vatterott & Vecera, 2012) and smartphone dependence (Ward et al., 2017). With regards to a limitation with the current study, there is still no direct physiological indicator of how attention was allocated as a function of WM load. A subsequent study should use electroencephalography to provide a more sophisticated answer with regards to the time course of selective attention. Neurophysiological studies have determined well-established neural markers of attentional deployment such as the early component N2pc roughly occurring 200ms after stimulus onset (e.g., Luck & Hillyard, 1994; Eimer, 1996; Hickey et al., 2009; Fuggetta & Duke, 2017) and the later contralateral delay activity indexing the number of representations being held in WM (Vogel & Machizawa, 2004; Vogel et al., 2005). It is more difficult to draw firm conclusions about attentional capture, since behavioural indices at the response stage reflect the cumulative effect of both early and late selection processes (Luck & Kappenman, 2012).

In conclusion, the main findings of the current experiment support Load Theory's (Lavie et al., 2004) WM load hypothesis regarding distractor interference effects to an extent. For instance, Load Theory's cognitive load predictions, in its purest form, cannot fully explain the plateau of ER effects when WM updating load reaches 3 to 4 items. The current findings can be explained by a combination of other theories such as Dilution Theory (Tsal & Benoni, 2010), the multi-component model (Baddeley & Hitch, 1974) and embedded processes model (Cowan, 2001) and of memory. The interplay between executive demands (WM load) and dilution can be identified under high load conditions. Here, additional items which have not reached the focused attention stage have diluted the representation of the distractor (Wilson et al., 2011). For the RT data, there was no support for Load Theory and showed a trend in the opposite direction. Subsequent investigations need to corroborate the findings from Load Theory to determine whether the effects of WM load, especially targeting a specific EF, can be upheld considering that the current evidence suggests that this is not always the case (Allen et al., 2017; Yao et al., 2020).

Chapter 3: Neural Correlates of Selective Attention in Distraction Suppression

3.1 Introduction

The concept of an attentional template has been investigated within the context of visual WM and selective attention (Desimone & Duncan, 1995). It has been defined as the enhanced status received by a visual item for a task, especially when it resembles a target stimulus. Many theories of attention posit that contents of visual WM guide attention towards relevant items (Bundesen, 1990). As an extension of Load Theory, Konstantinou and Lavie (2013) distinguished between different types of WM load in visual detection, i.e. visual maintenance and cognitive control functions of WM. The authors postulated that the ability to ignore distractors is influenced by the type of processing load involved in the current task. WM is a complex system in that it does not encompass only executive functions which have been associated with verbal WM load but also visual maintenance functions associated with visual and spatial WM tasks (Repovš & Baddeley, 2006). The central tenets of Load Theory are that 'WM cognitive control' is priority-based and that perception is capacity limited. When there is sufficient capacity for processing priorities within WM, this is allocated to relevant information. However, any excess capacity may spill over to the processing of irrelevant information. In conditions of high perceptual load, distractors were processed less due to reduced capacity. By loading VSTM, there will be an increase in demand for the sensory processing capacity in visual perception akin to what is involved in perceptual load. In high WM cognitive control load conditions, there is reduced availability to exert priority-based control over the task, and distractors are processed to a greater extent (Lavie et al., 2004). The extension of Load Theory terminology beyond perceptual load by these researchers can account for contradictory results in the literature (e.g., Ahmed & De Fockert, 2012a; 2012b).

In addition, Konstantinou and colleagues (2014) investigated the effects of loading VSTM at encoding and maintenance versus the effects of WM cognitive control load (verbal rehearsal).

Both types of load resulted in opposing directions: VSTM load reduced distractor effects, whilst cognitive load increased distractor effects. The VSTM task involved matching a memory probe colour or location to the initial colour memory sample. During this task, a response competition task with distractors was presented in the periphery. Longer RTs indexed the inability for participants to ignore the distractor. Cognitive control WM load conditions entailed stimuli consisting of either letters (active rehearsal) or meaningless symbols (which discouraged rehearsal) during the interleaved task. In line with previous findings (De Fockert et al., 2001; Lavie et al., 2004), distractor interference was greater in the verbal WM task during the memory delay period especially when active rehearsal was required. For VSTM load, the authors postulated that reduced distractor response competition effects were modulated by reduced perceptual processing of the distractor letters given that VSTM shares sensory visual representation resources with perception (Pasternak & Greenlee, 2005). The authors concluded that WM load can either interfere with or facilitate focused attention depending on whether maintenance or cognitive control functions were loaded.

In contrast with Load Theory, there is emerging evidence indicating that people were less distracted by irrelevant stimuli under high cognitive load because concentration on the current task ‘shielded’ against distraction when a task was more cognitively demanding (Sörqvist et al., 2016). The neurocognitive task-engagement/distraction trade-off theory (“TEDTOFF Theory”; Sörqvist & Rönnberg, 2014) incorporated WMC, i.e., individual differences in the ability to control attention and filter task-irrelevant information, as a critical factor which mediated distractibility. The TEDTOFF theory predicts that increased task difficulty, whether perceptual or cognitive, would decrease distractibility. Higher levels of cognitive load were found to correlate with enhanced focal-task engagement and the sensory gating of task-irrelevant information (Sörqvist & Marsh, 2015). Thus, individuals with high WMC have a more steadfast locus of attention and are less susceptible to the demands of background noise. Sörqvist and colleagues (2016) noted that the advantage for high-WMC individuals is not that they find completing a task easier but rather that they can achieve higher states of focal-task engagement whereby attention is fixated to the task and the influence of task-irrelevant information is attenuated (Sörqvist et al., 2012). The TEDTOFF model argues that manipulations of perceptual and WM load protect attentional processes against distraction.

Several previous studies have administered the Cognitive Failures Questionnaire (CFQ: Broadbent et al., 1982) which assesses minor slips of action, errors in memory and absent-mindedness occurring within the last 6 months, with 25 items (see Appendix I). The CFQ has high internal consistency (Cronbach's α= .91) and has a test-retest reliability of r=.82 over a 2-month interval (Vom Hofe et al., 1998). High scores in the CFQ have been related to serious outcomes such as incidences of car accidents (Wallace & Vodanovich, 2003) to minor mistakes of failing to save computer work (Jones & Martin, 2003). In studies of attention, high CFQ scorers also demonstrated high levels of distractibility (indexed by longer reaction times) in laboratory tasks (Burra & Kerzel, 2014; Kanai et al., 2011; Murphy & Dalton, 2014). Furthermore, a positive correlation between CFQ scores and the magnitude of the congruency effect (calculated by subtracting congruent RTs from incongruent RTs) has been found (Forster & Lavie, 2007).

3.1.1 Neural Correlates of Selective Attention

There are two ways in which attention can be oriented; either endogenously or exogenously (Buschman & Miller, 2007). Endogenous attentional orienting has been characterized as goal-driven, voluntary and effortful shifts which occur slowly. In contrast, exogenous attentional orienting has been described as involuntary, effortless and quickly executed shifts which may or may not aid the current goal (Theeuwes, 1991). Attentional capture is generally inferred from delayed reaction times in visual search tasks as a consequence of ‘reflexively’ shifting attention to a cue which was not target-related (Posner, 1980). Thus, the attentional capture debate has been fueled mainly by two opposing views: stimulus-driven versus goal-driven theories. According to stimulus-driven theories, the selection of visual objects is solely determined by bottom-up factors (e.g. physical salience) regardless of the observer’s intentions and that top-down control is only initiated at a later stage of processing (Theeuwes, 2004; 2010). On the other hand, goal-driven theories (Folk et al., 1992) assume that attention is only captured by stimuli containing features which match a search target (e.g. attentional set). Folk and colleagues (1992) have accepted that attentional capture can be ‘involuntary’ even after a top-down setting has been established. Their findings suggest that information unrelated to the current selection intentions, such as task instructions, can attract attention which is conceptually similar to inter-trial priming effects (Maljkovic & Nakayama, 1994). An alternative perspective is that attention is always captured by salient distractors but can be disengaged from quickly once they are deemed task-irrelevant and will not bias processing of subsequent visual items (Hickey et al., 2009; Sawaki & Luck, 2012; Theeuwes, 2010). A neuroimaging technique that is temporally sensitive to the dynamics of attentional processing is electroencephalography (EEG) which provides a continuous measure of brain activity with millisecond precision (Luck et al., 2000).

The Posterior Contralateral N2 Component (N2pc)

One of the most extensively studied ERPs in attentional processing is the N2pc component. Several studies have supported its role to reflect the attentional selection of potentially relevant items among distractors in visual search tasks via target enhancement or distractor suppression processes (Hickey et al. 2006; Theeuwes, 2010; Woodman & Luck, 1999; 2003). The N2pc component is characterized as an enhanced negativity over posterior scalp electrodes contralateral to the side of an attended stimulus. It is maximal around electrode PO7 for targets in the right visual field and PO8 for targets in the left visual field (Jolicœur et al., 2008). The N2pc component can be observed approximately between 150 and 300 ms after the onset of visual stimuli presentation (Luck, 2012). Both bottom-up (i.e. distractor salience; Hickey et al., 2006; Luck & Hillyard, 1994) and top-down (i.e. task relevance; Eimer, 1996; Eimer & Kiss, 2008; Lien et al., 2008; Mazza et al., 2009; Wykowska & Schubo, 2011) factors contribute to attentional capture. Early and late phases of the N2pc component have been distinguished (Eimer & Kiss, 2007; Holmes et al., 2009). The early N2pc has been associated with the initiation of an attentional shift, whereas the late N2pc has been linked to the filtering process of distractors (Fuggetta et al., 2006; Hopf, 2000). The subtraction method (contralateral minus ipsilateral side) used for the N2pc and related components aims to eliminate low-level processes and local noise from the waveform (Holmes et al., 2014). Several studies which have demonstrated visual WM manipulations on visual search, in terms of N2pc amplitude (e.g. Dell'Acqua et al., 2010; Eimer & Kiss, 2010; Feldmann-Wüstefeld & Vogel, 2019; Grubert & Eimer, 2016; Salahub et al., 2019).

Signal Suppression Hypothesis

The *signal suppression* hypothesis has been proposed to resolve the bottom-up/top-down debate of attentional capture (Gaspelin & Luck, 2019; Jannati et al., 2013; Sawaki & Luck, 2010). The signal suppression hypothesis is in agreement with stimulus-driven theories which assume that salient colour singletons will automatically capture visual attention via “attend-to-me” signals, irrespective of the observer’s goals (i.e. attentional set). However, there is a top-down inhibitory mechanism which suppresses the item before the initial shift of attention for further processing. Thus, this theory is not compatible with purely stimulus-driven theories which predicted attentional capture based on salience alone. Gaspelin and Luck (2018) postulate that suppression is guided by pre-attentive feature information which is a common characteristic in visual search models (Luck & Hillyard, 1994). According to Hickey and colleagues (2009), the N2pc component reflects a summation of two discrete ERP components: the Pd (distractor positivity) and the Nt (target negativity).

Pd (Distractor Positivity) Component

The Pd component was initially conceptualized by Hickey and colleagues (2009) when a positive voltage was observed at contralateral electrode sites compared to ipsilateral sites, relative to the position of the distractor stimulus. More specifically, participants were discriminating the identity of a target item in the presence of a distractor item. The Pd component does not reflect the attend-to-me signal, as it can be evoked by non-salient distractors. Several studies have demonstrated the Pd component as an electrophysiological marker of distractor suppression (Eimer & Kiss, 2008; Gaspelin et al., 2018; Kiss et al., 2012; Sawaki & Luck, 2012). Sawaki and Luck (2010) posited that its polarity is the opposite of the N2pc component and is eradicated when the experimental task requires detection rather than discrimination of target item identity. In some cases, even with salient distractors the Pd component can appear without the presence of an N2pc component (Sawaki & Luck, 2010). The time window of Pd ranges approximately between 100-440 ms (Burra & Kerzel, 2014; Hickey et al., 2009). Earlier intervals range from 100-300 ms (Gaspelin & Luck, 2018) whilst intermediate or later intervals were measured from 250-300 ms (Gaspar & MacDonald, 2014; Sawaki & Luck, 2011) or 300-350 ms (Hilmire et al., 2011; Kiss et al., 2012). The Pd component has been elicited by distractors in a WM task with an amplitude increase accompanying an increase in the number of distractors (Feldmann-Wüstefeld & Vogel, 2019). The increase in Pd amplitude was interpreted as more effortful suppression of items from entering WM.

Sustained Posterior Contralateral Negativity (SPCN)

A well-established ERP of visual WM engagement is the SPCN which indexes the amount of cognitive resources allocated for a task (Emrich et al., 2009). This lateralized late ERP component is interchangeably known as contralateral delay activity (CDA) which temporally succeeds the N2pc component (Luria et al., 2016; Vogel & Machizawa, 2004). The time window of the SPCN is approximately 300-650ms after stimulus presentation and persists for the duration of a task's retention interval (Jolicœur et al., 2006; 2008). The SPCN has been associated with several aspects of visual WM such as filtering (Vogel et al., 2005), maintenance and selection of information (Dell'Acqua et al., 2006; Nee & Jonides, 2008) as well as the number of representations held (Kang & Woodman, 2014; Luck & Vogel, 2013). Additionally, McCollough and colleagues (2007) found that the amplitude of SPCN was lowered on incorrect response trials as opposed to correct trials. A reduction in SPCN amplitude reflects lower demands of visual WM maintenance and target discrimination process (Eimer & Kiss, 2010; Jolicoeur et al., 2008). If the SPCN is insensitive towards task-relevant information, there should be no difference between conditions (Ikkai et al., 2010).

Early Visual Processing Components: P1 and N1

In particular, the P1 component has been defined as the enhanced sensory processing at attended locations regardless of whether the stimuli was a target or non-targets (Hillyard et al., 1998; Luck et al., 1994; Mangun & Hillyard, 1988). The mean voltage of this component can be quantified as a positive waveform between 90 and 120ms following a stimulus. Some authors have calculated the P1 as a difference between contralateral and ipsilateral electrode sites (relative to the cued location) such as the PO7/PO8 electrode sites used for the lateralized N2pc and Pd components (Sawaki et al., 2012).

As for the N1 component, this is another early visual evoked component indexing perceptual processing of an attended location but with a negative polarity (Luck et al., 2000). The mean voltage of this component can be quantified as a negative waveform between 140 and 200 ms following a stimulus (Hillyard & Anllo-Vento, 1998). The greater N1 amplitude component has been observed when deeper processing of visual information was required (Anllo-Vento & Hillyard, 1996). It has also been associated with the focusing of attention to relevant information (Luck et al. 1994; 2000).

The Anterior P2 Component

The anterior P2 component reflects the automatic detection of pop-out stimuli (Fuggetta & Duke, 2017; Luck & Hillyard, 1994) at 180-300 ms post-stimulus onset over prefrontal electrode sites (Potts, 2004). A larger anterior P2 waveform is found for target pop-outs compared to non-target pop-outs and homogeneous arrays. The occurrence of a P2 waveform is modulated by the presence of a specific and relevant feature rather than irrelevant features (Luck, 2012). This effect is pronounced when the presentation rate of target(s) is infrequent. The anterior P2 has been linked to the degree of match between the sensory input and representation stored in memory (Voss & Paller, 2009).

The P300 Component

The P300 component, specifically its latency, has been previously linked with the cognitive process of stimulus evaluation (Polich, 2007). The P300 has a wide time window (e.g., 250–500 ms, range dependent on factors such as stimulus modality or age) with a scalp distribution observed over the midline electrodes (Fz, Cz and Pz), which typically increases in magnitude from the frontal to parietal electrode sites. The ‘oddball’ paradigm is most often used to investigate the P300 and its dissociable subcomponents P3a and P3b, observed over anterior and posterior electrode sites respectively. Specifically, the P3a has been associated with stimulus probability and task relevance and has a brief time window of 250-280ms (Comerchero & Polich, 1999). The P3b has a more posterior scalp distribution, its amplitude indexes access to memory processes evoked by tasks which require context updating (Donchin & Coles, 1988). Picton (1992) has suggested that a P300 waveform can only occur if attention has been engaged in a task. In Kok's review (2001), smaller P3b amplitudes have been found with increased memory load in visual search tasks. Moreover, if a task requires less attentional resources, then there is a relatively large peak and shorter latency for the P300 (Kok, 2001; Scharinger at al., 2015).

3.1.2 Allocation of Visual Attention and Distractor Suppression

In relation to ERPs associated with visual spatial attention, Kehrer and colleagues (2009) provided electrophysiological evidence in a location negative priming (NP) paradigm. Location NP was defined as the slowing of responses to a previous distractor position which becomes the subsequent target position. NP effects were more potent in the easy task despite a general difficulty cost (indexed by increased RTs) in the difficult task. The main ERPs of interest included the N2pc, anterior N2 and P3. In both tasks, the amplitudes of N2pc and N2 were significantly enhanced for conflict trials, which was interpreted as greater exertion of cognitive control. The interpretation of enhanced anterior N2 amplitudes was that participants were more likely to engage their attentional set in the difficult task whilst increased top-down control was necessary to overcome the conflict in the easy task. Additionally, the latencies of N2pc and P3 were longer in the difficult task. The authors reasoned that increased latency for N2pc was a consequence of difficulty of selection (i.e. similarity between a target and distractor) which delayed the allocation of attention. The prolonged P3 latency with no significant differences in amplitude was regarded as delayed target evaluation.

Their experimental design specifically targeted attentional deployment for spatial position as opposed to object identity.

Recent work by Scharinger and colleagues (2015) examined the interplay between the inhibition and updating EF. The authors employed behavioral measures, pupil dilation and EEG data. The n-back task was used to induce WM load and is understood as primarily an updating EF task (Niendam et al., 2012). In line with the TEDTOFF theory, it was found that task performance was less susceptible to distraction under conditions of increased load on the updating EF. The authors explained that the decreased distractor interference and pupil dilation were due to the internal distribution of attention, as indicated by reduced posterior P300 amplitude. When both EF were required for a task, attentional resources were assumed to be distributed among inhibition and updating functions. Another notable finding was that shielding from distraction can occur within the same modality (i.e. stimuli that load onto both updating and inhibition in the visual domain) unlike previous studies which have manipulated across modalities. Additionally, the results reinforce previous findings that updating and inhibition EF share underlying network structures which serve attentional control (Miyake et al., 2000). It was found that participants were able to shield against distracting flanker letters as a result of enhanced attentional focus and inhibitory control processes. Multiple studies which have used the n-back task have demonstrated reduced P300 amplitude with increasing WM load (Chen et al., 2008; Kim et al., 2017; Pratt et al., 2011; Watter et al., 2001).

Fuggetta and Duke (2017) have previously investigated the time course of ERP components which play a role in the operation of visual attention. The authors employed a novel paradigm which combined a match-to-sample task with efficient visual search. They investigated the following ERPs which were similar to the current study: anterior P2, parieto-occipital N1 and N2pc. The focus of the study was to elucidate attention mechanisms which underlie the enhancement in behavioural performance with practice. For the early phase of the N2pc, there was a reduction in onset latency, suggesting that the time required to initiate the shift of attention was shorter with practice (similar to Clark et al., 2015). In addition, a greater peak amplitude and mean amplitude was found for the N2pc, which implies that there was an improvement in processing task-relevant input and suppressing irrelevant features. Related studies which have adopted this similar paradigm have included a task-irrelevant display in which a spatial cue would grab attention either to the centre (Bennett et al., 2014) or to the periphery (Fuggetta et al., 2015) of the screen. Fuggetta and colleagues (2015) were particularly interested in the modulation of schizotypy (schizotypal personality traits and likelihood of developing psychosis) and found that the late phase of N2pc magnitude was larger and its peak latency was significantly delayed for individuals scoring high in the schizotypy questionnaire. The interpretation of results was that the combination of tasks must have strained attentional control processes to a greater extent, such as the implementation of selection process (Luck & Gold, 2008). For these individuals, the ability to enhance task-relevant features of a target and suppress irrelevant input has been impaired (indexed by a decreased N2pc amplitude) which was correlated with an increase in ‘Cognitive Disorganisation’ scores.

3.1.3 Study Aims

A primary aim of the current study was to test investigate WM load effects by pitting the predictions from Load Theory (Lavie et al., 2004) against the TEDTOFF theory (Sörqvist & Rönnberg, 2014) as the latter has been directly investigated with EEG (i.e. Scharinger et al., 2015) and can help scaffold a balanced debate within the literature. The predictions of the current study were bi-directional such that increased WM load may lead to greater or reduced distractor interference. The first predicted outcome, in line with Load Theory, is increased distractor interference effect because high WM load impairs attentional control processes (Konstantinou & Lavie, 2013; Roper & Vecera, 2014). The second predicted outcome was decreased distractor interference effect under high WM load which protects against distraction (Sörqvist & Marsh, 2015; Simon et al., 2016). However, these aforementioned studies focus on WM load effects under dual-task conditions. To date, a few studies have investigated the interplay between the inhibition and updating EF using a different EF task, i.e. n-back task (Scharinger et al. 2015; 2017; Kim et al., 2017). The current experiment extended a previous electrophysiological study Fuggetta and colleagues (2015) by embedding a distractor singleton within a visual search array during the retention interval. A key difference is that the distractor would either match/mismatch the initial sample and subsequent target whereas the colour of distractors always differed from the target stimulus (Bennett et al., 2014; Fuggetta et al., 2017).

The current study operationalized WM load in terms of loading the *updating* EF and examining its effects on the *inhibition* EF of distracting stimuli (Friedman & Miyake, 2017). This chosen model of EF offers an intermediate level of complexity with which to examine the question of unity and diversity (McCabe et al., 2010). The current study used a modified delayed match-to-sample task (Fuggetta & Duke, 2017; Wang et al., 2004) requiring the updating and monitoring of information in WM by varying the set-size within a task (Konstantinou & Lavie, 2013). This paradigm incorporates an efficient visual search task (Wolfe, 1994; Barras & Kerzel, 2017) with a singleton feature 'pop-out' for spatial position and object identity amongst an array of homogeneous non-target shapes (Treisman & Gelade, 1980).

Thirdly, the current experiment aimed to enhance the understanding of event-related potentials (ERPs) associated with visual WM and selective attention, i.e. the cognitive processes underlying susceptibility to distraction mediated by WM load. A disadvantage of behavioral measures (reaction times and accuracy) alone is that they reflect the summation from both early and late selection mechanisms (Luck & Kappenman, 2012). The present combination of tasks allows a wider scope of examining the time course of cognitive processing, as indexed by ERPs, than those afforded by the traditional visual search paradigm. The inclusion of WM load conditions within Fuggetta & Duke's (2017) paradigm allowed for the examination of the SPCN. The midline P300 was taken into account following previous investigations specific to the interplay between Updating and Inhibition EF (Kim et al., 2017; Scharinger et al., 2015). The neural correlate of primary interest was the N2pc component which reflects the enhancement of attentional processing (Luck & Hillyard, 1994; Luck, 2012) and heavily influenced the design of the experiment i.e. distractor and target items were always lateralised. The direction of WM load effects on the amplitude of P1, N1, anterior P2, N2pc, Pd, midline P300 and SPCN waveforms were bi-directional given the opposing predictions of the aforementioned theories of attention and the use of a novel paradigm.

The primary hypotheses were focused on the direction of distraction interference effects based on two existing dominant theories: increase according to Load Theory (Lavie et al., 2004) whereas a reduction was posited by the TEDTOFF theory (Sörqvist & Rönnberg, 2014), with greater WM load. The other primary hypothesis was specific to the N2pc component (Luck & Hillyard, 1994; Luck, 2012) in that it was anticipated to occur using a similar task (Fuggetta & Duke, 2017). The amplitude of the N2pc and Pd components could follow the predictions of either Load Theory (Lavie et al., 2004) or the TEDTOFF theory (Sörqvist & Rönnberg, 2014) depending on the WM load condition. The secondary hypotheses concerned the other ERP components of interest such as the P1, N1, anterior P2 and SPCN (Fuggetta & Duke, 2017). The midline P300 was of particular interest as a reduction in amplitude could reflect an interplay between the Updating and Inhibition EF (Scharinger et al., 2015). In line with Forster and Lavie (2007), the secondary hypothesis involves replicating the correlation between the CFQ scores and distractor interference effect and the electrophysiological measures of distractor interference i.e., the N2pc component (Fuggetta & Duke, 2017).

3.2 Method

3.2.1 Participants

The sample size (*N*=53) for Experiment 2 was a priori calculated using G*power 3.1. (Faul et al., 2007) for the repeated measures ANOVA, with an expected medium effect size (η2 = 0.06), power of .95, and alpha level of .05. 71 volunteers started the experiment and had given written informed consent. 16 participants were excluded to control for confounding variables; a) those who did not complete all cognitive tasks, b) had an existing scalp skin condition c) reported any history of, or are taking medication for, psychiatric or neurological disorders or diseases (e.g., ADHD, depression, anxiety, mood disorders, or epilepsy), d) colour-blindness, e) with EEG data with less than 50% of total trials after artefact removal and f) were not 18-40 years of age. The final sample of 55 participants had normal or corrected-to-normal vision (*M* age = 20.64 years, range = 18-36 years, *SD* = 3.42, 42 females, 2 left-handed). Participants were students recruited from the University of Roehampton's Psychology department and participation was awarded with course credit. Full debriefing was given to participants at the end of the experiment (Appendix E). Ethical approval was granted by the ethics committee of University of Roehampton.

3.2.2 Materials and Procedure

Cognitive Failures Questionnaire (CFQ: Broadbent et al., 1982) which assesses minor slips of action, errors in memory and absent-mindedness occurring within the last 6 months. The CFQ has high internal consistency (Cronbach's α= .91) and has a test-retest reliability of *r*=.82 over a 2-month interval (Vom Hofe et al., 1998). The CFQ is a 25-item scale whereby all items can be summed for a total score. The three-factor model of the CFQ comprises three different subscales: Forgetfulness, Distractibility and False Triggering in addition to the total score (Rast et al., 2009). Forgetfulness represented the likelihood of letting known or planned thoughts (e.g. names). Distractibility reflected the disruption of focused attention due to absent-mindedness especially in social situations. False Triggering was a factor associated with interrupted of cognitive and motor actions. See Appendix I for a full list of items.

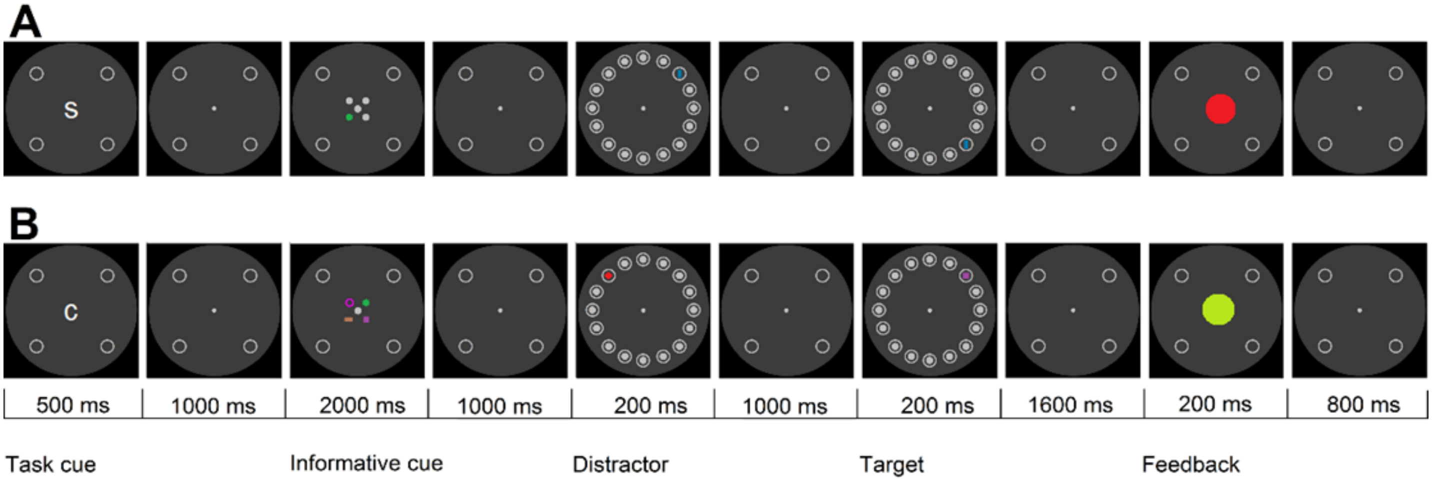
Visual task The DMTS task used was similar to Experiment 1 with a few minor adjustments such as the WM load conditions were determined by previous literature (Cowan, 2001) and Experiment 1. There were two conditions of WM load; either low (one item to rehearse in WM) or high (four items to rehearse in WM). A control condition was introduced whereby by the distractor array consisted only of homogeneous white circles with no pop-out singleton. Participants completed twelve blocks of 64 trials (N=768) and were allowed to take breaks between blocks. The sequence of events was exactly the same as Experiment 1 (refer to Figure 3.1) except for the following differences. Firstly, the task cue was either a 1.2^o x 1.2^o white (20.97 cd/m2) “C” or “S”, at the beginning of each trial, depending on the match-to-sample task (shape or colour). A visual feedback display; either “Correct” (bright green smiley face: 29.93cd/m2), “Incorrect” and “No response” (bright red sad face: 30.16 cd/m2) replaced the previous auditory feedback at the end of each trial. The RGB values can referred to in Appendix F(ii).

Participants were naïve to the aims of the experiment. All participants were tested individually in a dimly lit room and completed the computer task for approximately 1 hour whilst the EEG electrode set-up lasted 40 minutes. To reduce head motion, a chin-rest was used for each participant with a fixed viewing distance of 71 cm. Participants completed 16 practice trials to familiarise themselves with the task before the main experimental phase. The practice trials were repeated until the average accuracy was 65% or above to avoid performance at chance level.

Participants were instructed to fixate on the screen throughout trials. They were told to respond as quickly and accurately as possible using a mouse. Behavioural measures of task performance and scalp recorded EEG were recorded simultaneously. Questionnaire data was collected along with the EEG and behavioural results. Although the questionnaire data was not relevant to the main aim of the PhD thesis, it can be used to conduct exploratory analysis for future research. Exploratory analysis of the association between cognitive failures in everyday life (Broadbent et al., 1982) with the magnitude of distractor interference effect (both in the behavioural and electrophysiological measures), in the current study, can be found in Appendix I. An in-house experiment generator software programmed with Lazarus (https://www.lazarus-ide.org/) was used to present the experiment on a 24" LCD monitor (AOC G2460PG G-SYNC) with 1 ms response time, a resolution of 1920 x 1080 pixels and a refresh rate of 100 Hz.

Figure 3.1

Example of sequence of events of two trials of the visual task varying the *updating* EF load.



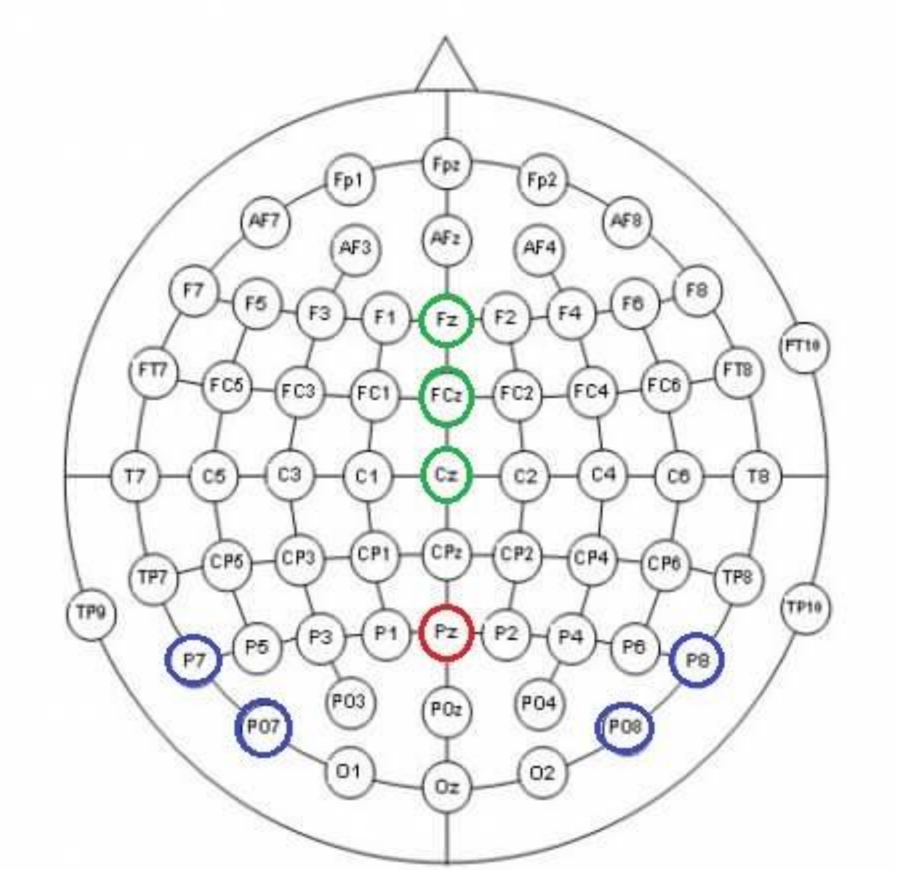
Note. (A) This trial is an example of the shape task, low WM load and incongruent condition. This is because the task cue is “S”, the informative cue has one shape to be rehearsed in WM and the distractor is different from the target shape. (B) This trial is an example of the colour task, high WM load and congruent condition. This is because the task cue is “C”, the informative cue has four shapes to be rehearsed in WM and the distractor is similar to the target colour. Please note that the task was kept constant within blocks of trials. For illustrative purposes, the feedback shapes are simple circles and were different in the experiment.

3.2.3 EEG Data Acquisition

Continuous EEG signals were recorded using the 64-channel Biosemi ActiveTwo EEG system (BioSemi, Amsterdam, Netherlands), using a quickcap following the extended 10/20 system at a sampling rate of 2048 Hz. Horizontal electrooculograms were recorded via flat-type electrodes placed 1cm from the outer canthi of both eyes. Vertical electrooculograms and blinks were recorded using two electrodes; one placed above and one below the left eye. There were an additional two electrodes placed on each earlobe. After the application of electrode gel, pin-type electrodes mounted in place with an elastic cap (refer to Figure 3 for electrode layout). In contrast to other EEG systems, the ActiveTwo system allows for reference-free recording of EEG signals (Hairston et al., 2014). Instead, the ground reference is regulated by two electrodes (DRL/CMS) that provide a feedback loop that acts to regulate the current from the participant to the AD Box. EEG waveforms were re-referenced offline to the Common Average Reference (CAR). Artifacts such eye movements, muscular contractions and electrode artefacts were excluded by visual inspection of the data via ICA. BrainVision Analyzer 2 software (Brain Products GmbH) was used to remove trials and channels with low signal-to-noise ratio including the interpolation of bad electrode channels. Channels containing artifacts over prolonged periods were completely excluded from further analyses. ERPs were filtered using a 0.01Hz high-pass, 46Hz low-pass and 50Hz notch filter. EEG was epoched from 200ms prior to search array onset (i.e. distractor array) and 800ms after array onset. Normalised ERP values using the 200 ms prior to search array onset as baseline period with a 10 ms resolution were computed using Matlab.

***Figure* 3**

10-20 system montage of 64 channels retrieved and adapted from EASYCAP GmbH: **easycap.de**.



Note. Electrode sites for midline anterior component: P2 (green), midline parietal component: P300 (red), the lateralized and bilateral parieto-occipital components: P1, N1, N2pc, Pd and SPCN (purple) regions included in statistical analyses of mean amplitudes.

3.2.4 Experimental Design

The independent variables were WM load (i.e. set-size one and four to rehearse in WM) and Distractor Type (mismatching initial sample, matching initial sample). The behavioural dependent variables were reaction times (milliseconds) and error rates (%). The electrophysiological dependent variables were the P1, anterior P2, N1, N2pc, Pd, SPCN and midline P300 components. The magnitude of distractor interference effect of the initial sample on the distractor (S2) was computed by subtracting the task performance between the following two conditions: Distractor Type Mismatching minus Distractor Type Matching. To minimize any involvement of the shifting EF, shape/colour task were presented in pure blocks. The reason for employing a feature ‘pop-out’ search array (Treisman & Gelade, 1980) was to make attentional guidance processes towards the location of the task-relevant item easier to occur. Distractor (S2) and target (S3) items remain as singletons to control for perceptual load. Task was not considered as factor for two reasons: the effect of task was beyond the scope of the main research question and the stimuli were perceptually identical in both tasks. Distractor interference will be indexed through the reaction times to the target as a function of the distractor’s congruency with the initial sample. Distractor interference is inferred from the slowing down of reaction times in the presence of mismatching distractors as compared with matching distractors.

3.3 Results

In all ANOVAs, Greenhouse-Geisser epsilon adjustments were applied for cases of non-sphericity. As for post-hoc paired t-tests, multiple comparisons were Bonferroni corrected. A two-tailed hypothesis was used therefore Alpha = .05. To ensure consistency with the ERP data which have included lateralised components (i.e. N2pc, Pd, SPCN), the control condition of homogeneous displays were not included in the statistical analysis of both behavioural and ERP results. All statistical analyses were performed using Statistical Package for the Social Sciences Statistics (SPSS Version 26, IBM). The analysis of behavioural data, the N2pc and Pd components addresses the primary hypotheses as aforementioned (see section 3.1.3). The analysis of the SPCN, P1, N1, anterior P2, midline P300 and CFQ correlations addresses the secondary hypotheses.

3.3.1 Behavioural Data

Only correct responses and RTs longer than 150 ms were analysed with 1.5% of trials removed from analysis. Responses longer than 1800 ms were logged by the system as omissions. RT and error rates were analysed with a 2-way repeated measures ANOVA. The within-subjects factors were WM load (low, high) and Distractor Type (mismatching the initial sample, matching the initial sample). Mean RTs and error rate values can be found in Table 3.1. The analysis was combined rather than splitting the variables by task (i.e., colour and shape).

Table 3.1

Mean RTs (milliseconds) and Mean Error Rates (%) by WM Load and Distractor Type.

RTs/ Error Rates	Load 1	Load 4
Distractor Type_Mismatching	652.07 (112.85)	765.97 (113.21)
Distractor Type_Matching	621.83 (107.26)	751.99 (115.39)
Distractor Type_Mismatching	10.02 (6.67)	33.11 (9.91)
Distractor Type_Matching	7.80 (5.67)	23.41 (8.72)

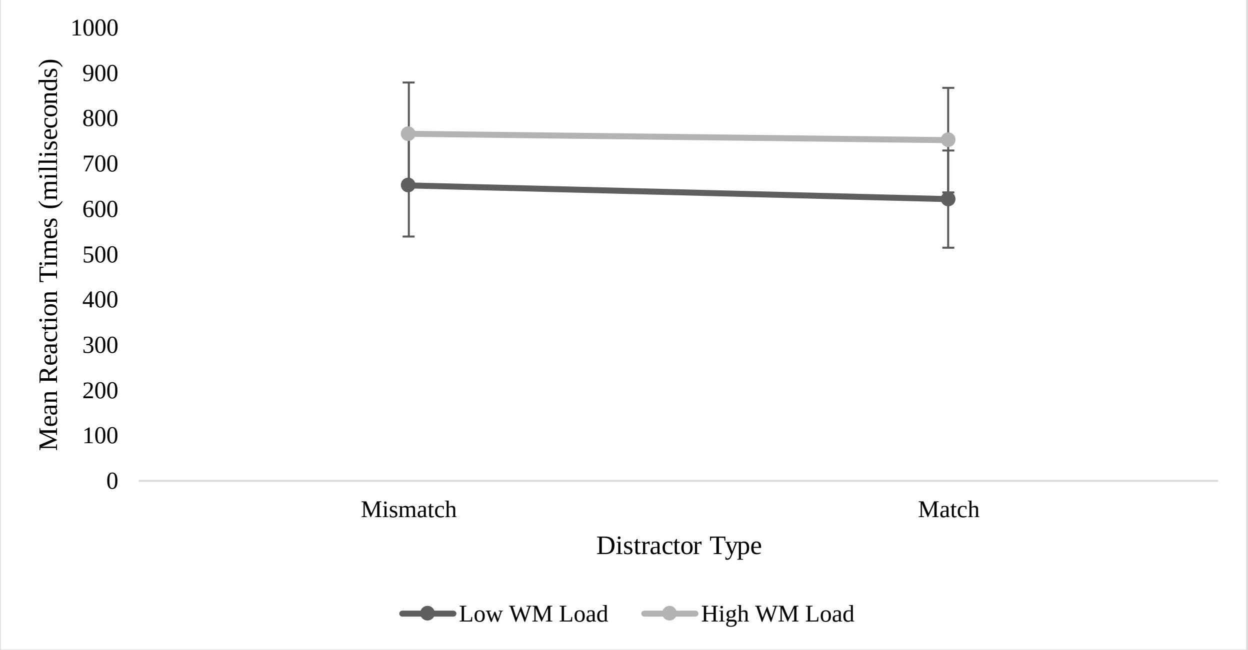
Note: Standard Deviation values are shown in parentheses.

Reaction Times

ANOVA of RTs revealed a significant main effect of WM Load $F(1, 54) = 275.54$, $p < .001$, $\eta_p^2 = .84$ showing that participants were slower to respond to the high WM load condition (M=758.98, SE=15.27) than the low WM load condition (M=636.95, SE=14.72). There was a significant main effect of Distractor Type $F(1, 54) = 89.59$, p<.001, $\eta_p^2 = .62$ revealing that participants were slower to respond to mismatching distractors (M=709.02, SE=14.60) than matching distractors (M=686.91, SE=14.57). There was a significant interaction between WM Load x Distractor Type $F(1, 54) = 6.20$, p=.016, $\eta_p^2 = .10$. Post-hoc comparisons showed that for both low and high WM load conditions, RTs were significantly different between each type of distractors. Under low WM load, means differed significantly between mismatching and matching distractors (*MD*= 30.25, *SE*=3.82, *p*<.001). Under high WM load, means differed significantly between mismatching versus matching distractors (*MD*= 13.97, *SE*= 4.21, *p*=.002). This interaction demonstrated that there was a smaller congruency effect in the high WM load condition.

Figure 3.2a

Mean RTs by Distractor Type (in relation to WM conditions).



Error Rates

ANOVA of error rates revealed a significant main effect of WM Load *F*(1, 54) =577.19, p<.001, η_p^2 =.91 showing that participants made more errors under the high WM load condition (*M*=28.3, *SE*=1.1) than the low WM load condition (*M*=8.9, *SE*=0.8). There was a significant main effect of Distractor Type *F*(1, 54) =81.39, p<.001, η_p^2 =.60 revealing that participants were least accurate to respond to mismatching distractors (*M*=21.6, *SE*=1.0) than matching distractors (*M*=15.6, *SE*=0.9). The two-way interaction WM Load x Distractor Type *F*(1, 54) =46.63, *p*<.001,

η_p^2 =.46 was significant. Post-hoc comparisons revealed that for the low WM load condition, error rates significantly differed for mismatching versus matching distractors (*MD*= 2.2, *SE*=0.6, *p*<.001. Under high WM load, means differed significantly between mismatching versus matching distractors (*MD*= 9.7, *SE*= 1.1, *p*<.001). This interaction demonstrated that there was a greater congruency effect in the high WM load condition.

Figure 3.2b

Mean Error Rates by Distractor Type (in relation to WM conditions).

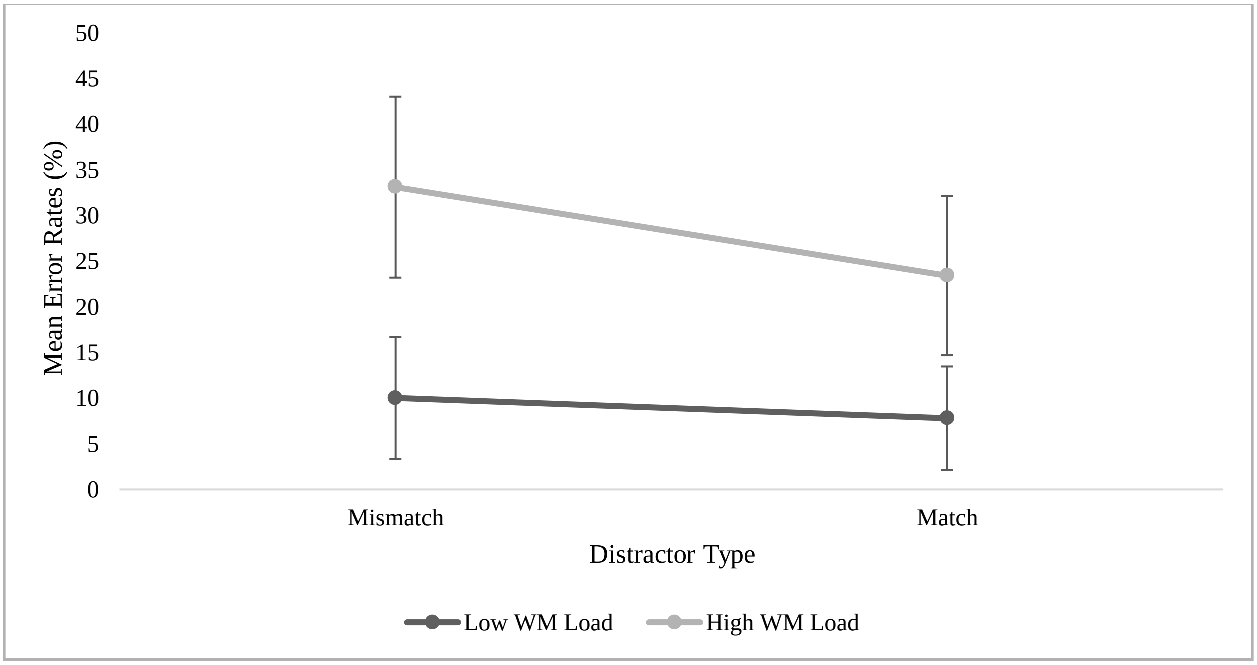


Table 3.2
Mean Congruency Effect of RTs (milliseconds) and Mean Error Rates (%) by WM Load.

RTs/ Error Rates	Mean Difference (Mismatching minus Matching)
Load 1	30.25 (28.31)
Load 4	13.97 (31.21)
Load 1	2.22 (4.12)

RTs/ Error Rates	Mean Difference (Mismatching minus Matching)
Load 4	9.70 (8.0)

Note: Standard Deviation values are shown in parentheses.

Distractor Interference Effect

Similar to Kelley & Lavie (2010), the distractor congruency effect (incongruent minus congruent) was computed. The t-test results for RTs revealed that the distractor congruency effect (*MD*= -16.27, *SD*= 6.54) was significantly greater under low WM load than high WM load *t*(54)=2.49, *p*= .02. The t-test results for error rates revealed that the distractor congruency effect (*MD*= 7.48, *SD*= 8.12) was significantly greater under high WM load than low WM load *t*(54)=-6.83, *p*< .001.

3.3.2 Electrophysiological Data

Separate average ERPs (mean µV) were computed for the lateral parieto-occipital electrodes; P7, P8, PO7 and PO8. To isolate the magnitude of the N2pc, Pd and SPCN component elicited by the **distractor singleton array (S2)**, difference waves were calculated by subtracting ipsilateral from contralateral electrodes P7/8 and PO7/8 relative to the distractor (singleton) location. These electrodes were chosen for analysis because contralaterality effects were most pronounced at these sites as in previous studies (Luck & Hillyard, 1994; Hickey et al., 2009; Sawaki & Luck, 2010). A 3-way repeated measures ANOVA with the within-subjects factors; WM load (low, high), Distractor Type (mismatching, matching) and Electrode (P7/P8, PO7/PO8) at S2 (i.e., distractor array onset) was carried out for each lateralised ERP component.

3.3.2.1 N2pc: 170-249 ms (Eimer, 2007; Holmes et al., 2009; Li et al. 2017)

Table 3.3

ANOVA Results within the N2pc Time Window Normalized ERP Values at S2.

Source	*Df*	*F*	Sig.	Partial Eta Squared
Load	**1, 54**	**15.12**	**<.001**	**.22**
DT	1, 54	0.13	.72	.002
Electrode	1, 54	0.41	.52	.008
Load * DT	1, 54	0.32	.58	.006
Load * Electrode	1, 54	0.06	.82	.001
DT * Electrode	1, 54	1.09	.30	.02
Load * DT * Electrode	1, 54	0.19	.67	.003

Note: T = Task, Load= Working Memory Load, DT= Distractor Type and *Df*= degrees of freedom. Significant main effects and interactions are bolded.

ANOVA of mean amplitude values within the N2pc time window revealed only a significant main effect of WM load $F(1, 54) = 15.12$, $p < .001$, $\eta_p^2 = .22$ in that the mean amplitude was more negative under low WM load (*M*= -.51, *SE*= 0.12) versus high WM load (*M*= -.12, *SE*= 0.08). There were no other significant main effects and interactions (*ps*> .05).

3.3.2.2 Pd: 320-359 ms (Burra & Kerzel, 2014; Hickey et al., 2009; Sawaki et al., 2012)

Table 3.4

ANOVA Results within the N2pc Time Window Normalized ERP Values at S2.

Source	*Df*	*F*	Sig.	Partial Eta Squared
Load	**1, 54**	**5.08**	**.03**	**.09**
DT	1, 54	0.002	.97	<.001
Electrode	1, 54	1.30	.26	.02

Source	*Df*	*F*	Sig.	Partial Eta Squared
Load * DT	1, 54	3.35	.07	.06
Load * Electrode	1, 54	0.01	.92	<.001
DT * Electrode	1, 54	0.67	.42	.01
Load * DT * Electrode	1, 54	0.14	.71	.003

Note: T = Task, Load= Working Memory Load, DT= Distractor Type and *Df*= degrees of freedom. Significant main effects and interactions are bolded.

ANOVA of mean amplitude values within the Pd time window revealed only a significant main effect of WM load *F*(1, 54) =5.08, *p*= .03, η_p^2 =.09 in that the mean amplitude was more negative under low WM load (*M*= 0.37, *SE*= 0.12) versus high WM load (*M*= 0.62, *SE*= 0.11). No other main effects and interactions were significant (*ps*> .05).

3.3.2.3 SPCN: 480-549 ms (Berggren & Eimer, 2018; Eimer & Kiss, 2010; Jolicoeur et al., 2008)

Table 3.5
ANOVA Results within the SPCN Time Window Normalized ERP Values at S2.

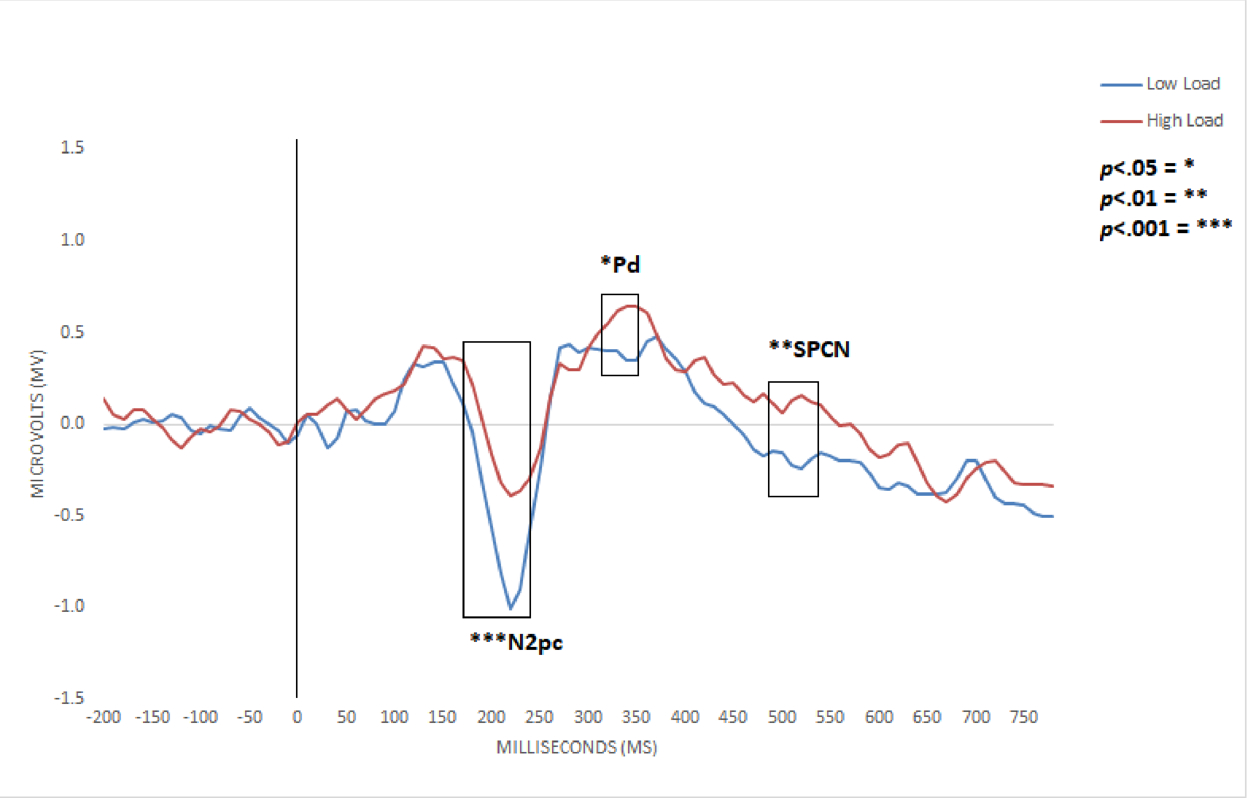
Source	*Df*	*F*	Sig.	Partial Eta Squared
Load	**1, 54**	**7.21**	**.01**	**.12**
DT	1, 54	1.03	.32	.02
Electrode	1, 54	1.05	.31	.02
Load * DT	1, 54	3.35	.07	.006
Load * Electrode	1, 54	0.93	.34	.02
DT * Electrode	1, 54	3.40	.07	.06
Load * DT * Electrode	1, 54	<.001	1.0	<.001

Note: T = Task, Load= Working Memory Load, DT= Distractor Type and *Df*= degrees of freedom. Significant main effects and interactions are bolded.

ANOVA of mean amplitude values within the SPCN time window revealed only a significant main effect of WM load *F*(1, 54) =7.21, *p*= .01, η_p^2 =.12 in that the mean amplitude was more negative under low WM load (*M*= -.18, *SE*= 0.09) versus high WM load (*M*= .12, *SE*= 0.09). All other main effects and interactions were not significant (*ps*> .05).

Figure 3.3

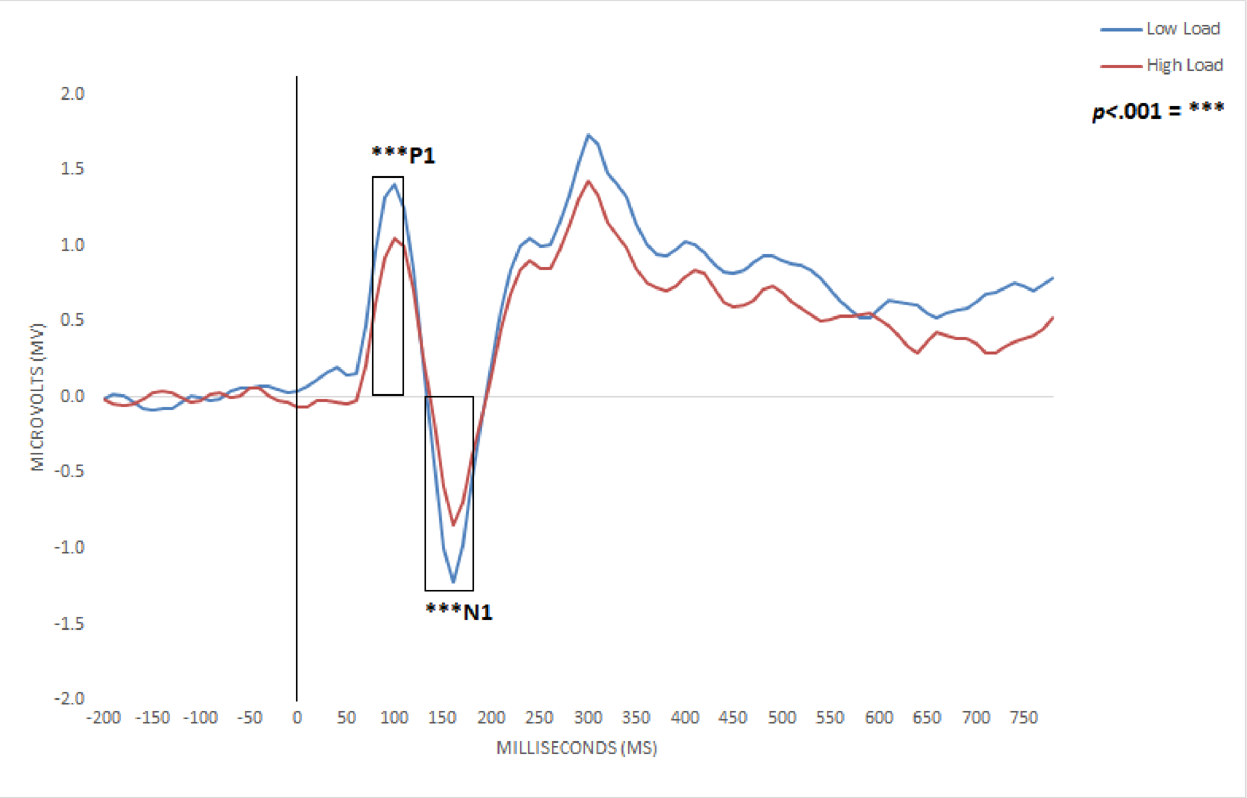
Time Course of Mean Amplitude at Parieto-Occipital Electrode Sites (P7/8, PO7/8) by WM Load with the Lateralised Components: 170-249 ms (N2pc), 320-359 ms (Pd) and 480-549 ms (SPCN) Intervals Depicted.



Separate average ERPs (mean µV) were computed for the bilateral parieto-occipital electrode pairs; P7-P8 and PO7-PO8. A 3-way repeated measures ANOVA with the within-subjects factors; WM load (low, high), Distractor Type (different, same) and Electrode Pair (P7/P8, PO7/PO8) at distractor array onset was carried out for the bilateral ERP components.

Figure 3.4

Time Course of Mean Amplitude at Parieto-Occipital Electrode Sites (P7/8, PO7/8) by WM Load with the Bilateral Components: 70-119 ms (P1), 140-189 ms (N1) Intervals Depicted.



3.3.2.4 P1: 70-119 ms (Vogel & Luck. 2000; Woodman, 2010)

Table 3.6
ANOVA Results within the P1Time Window Normalized ERP Values at S2.

Source	*Df*	*F*	Sig.	Partial Eta Squared
Load	**1, 54**	**15.32**	**<.001**	**.22**
DT	1, 54	0.92	.34	.02
Electrode	**1, 54**	**5.49**	**.02**	**.09**
Load * DT	1, 54	0.004	.95	<.001
Load * Electrode	1, 54	2.82	.10	.05
DT * Electrode	1, 54	0.24	.63	.004
Load * DT * Electrode	1, 54	0.005	.94	<.001

Note: T = Task, Load= Working Memory Load, DT= Distractor Type and *Df*= degrees of freedom. Significant main effects and interactions are bolded.

ANOVA of mean amplitude values within the P1 time window revealed a significant main effect of WM load $F(1, 54) = 15.32$, $p < .001$, $\eta_p^2 = .22$ in that the mean amplitude was more positive under low WM load (*M*= 1.24, *SE*= 0.14) versus high WM load (*M*= .90, *SE*= 0.11). There was a significant main effect of Electrode Pair $F(1, 54) = 5.49$, $p = .02$ $\eta_p^2 = .09$ in that the mean amplitude was more positive for PO7/8 (*M*= 1.16, *SE*= 0.14) versus P7/8 (*M*= .97, *SE*= 0.10). All other main effects and interactions were not significant (*ps*> .05).

3.3.2.5 N1: 140-189 ms (Berggren & Eimer, 2018; Vogel & Luck, 2000)

Table 3.7
ANOVA Results within the N1 Time Window Normalized ERP Values at S2.

Source	*Df*	*F*	Sig.	Partial Eta Squared
Load	**1, 54**	**9.64**	**.003**	**.15**
DT	1, 54	0.03	.86	.001
Electrode	**1, 54**	**7.97**	**.007**	**.13**
Load * DT	1, 54	0.002	.96	<.001
Load * Electrode	**1, 54**	**5.32**	**.03**	**.09**

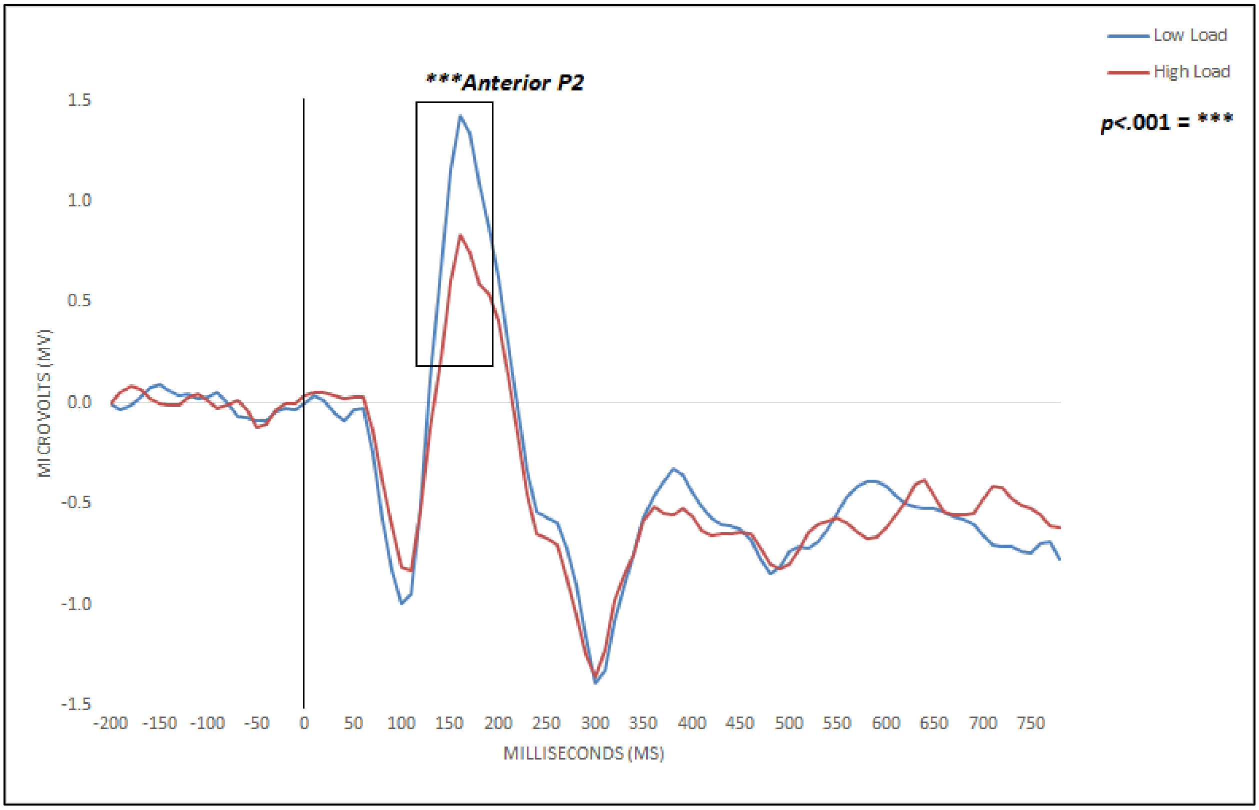
Source	*Df*	*F*	Sig.	Partial Eta Squared
DT * Electrode	1, 54	0.25	.62	.005
Load * DT * Electrode	1, 54	1.14	.29	.02

Note: T = Task, Load= Working Memory Load, DT= Distractor Type and *Df*= degrees of freedom. Significant main effects and interactions are bolded.

ANOVA of mean amplitude values within the N1 time window revealed a significant main effect of WM load $F(1, 54) = 9.64$, $p = .003$, $\eta_p^2 = .15$ in that the mean amplitude was more negative under low WM load ($M = -.83$, $SE = 0.16$) versus high WM load ($M = -.53$, $SE = 0.14$). There was a significant main effect of Electrode Pair $F(1, 54) = 7.97$, $p = .007$, $\eta_p^2 = .13$ in that the mean amplitude was more negative for PO7/8 ($M = -.79$, $SE = 0.17$) versus P7/8 ($M = -.57$, $SE = 0.12$). There was a significant WM load x Electrode Pair interaction $F(1, 54) = 5.32$, $p = .03$, $\eta_p^2 = .09$. Post-hoc comparisons showed that for both low and high WM load conditions, mean amplitudes were significantly different between each pair of electrodes. For both electrode pairs P7/8 ($MD = -0.23$, $SE = 0.11$, $p = .04$) and PO7/8 ($MD = -0.38$, $SE = 0.10$, $p < .001$), the mean amplitude was more negative under low WM load than high WM load. All other main effects and interactions were not significant (*ps*> .05).

Figure 3.5

Time Course of Mean Amplitude at Midline Electrode Sites (Fz, FCz, Cz) by WM Load with the 130-199 ms (Anterior P2) Interval Depicted.



3.3.2.6 Anterior P2: 130-199 ms (Fuggetta & Duke, 2017)

The repeated measures ANOVA of the anterior P2 component consisted of three within-subjects factors; WM load (low, high) and Distractor Type (different, same) and Electrode (Fz, Fcz, Cz).

Table 3.8

ANOVA Results within the Anterior P2Time Window Normalized ERP Values at S2.

Source	*Df*	*F*	Sig.	Partial Eta Squared
Load	**1, 54**	**21.21**	**<.001**	**.28**
DT	1, 54	0.83	.37	.02
Electrode	1.21, 65.57	2.59	.11	.05
Load * DT	1, 54	0.87	.77	.002
Load * Electrode	1.51, 81.41	2.87	.08	.05
DT * Electrode	1.56, 84.20	0.02	.95	<.001

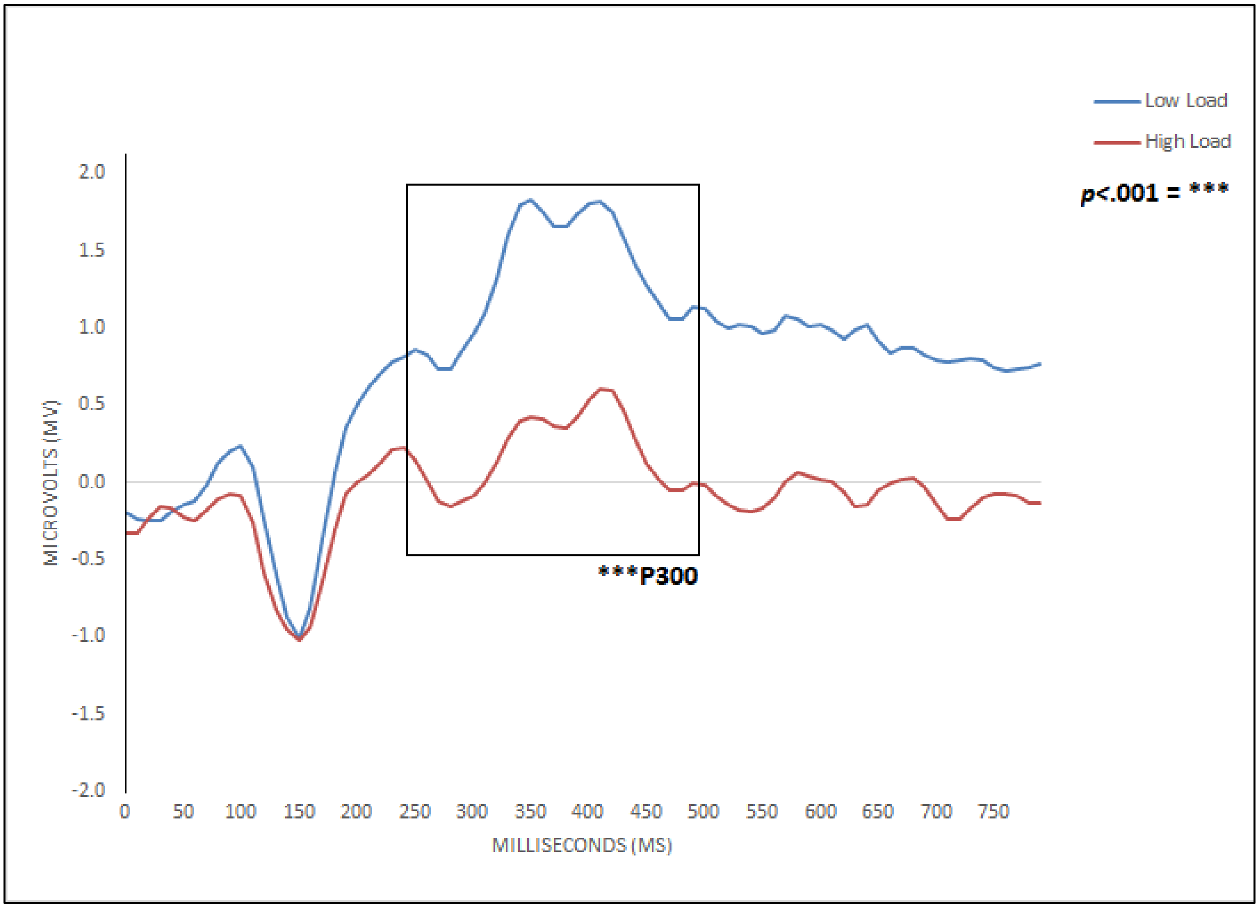
Source	*Df*	*F*	Sig.	Partial Eta Squared
Load * DT * Electrode	1.44, 77.56	1.83	.18	.03

Note: T = Task, Load= Working Memory Load, DT= Distractor Type and *Df*= degrees of freedom. Significant main effects and interactions are bolded.

ANOVA of mean amplitude values within the anterior P2 time window revealed only a significant main effect of WM load *F*(1, 54) =21.21, *p*< .001, η_p^2 =.28 in that the mean amplitude was more positive under low WM load (*M*= 0.96, *SE*= 0.15) versus high WM load (*M*= 0.49, *SE*= 0.12). No other main effects and interactions were significant (*ps*> .05).

Figure 3.6

Time Course of Mean Amplitude at Midline Electrode Pz by WM Load Encompassing the 250-500 ms (P300) Interval.



3.3.2.7 P300: 250-500 ms (Polich, 2007; Scharinger et al., 2015; Watter et al., 2001)

The analysis for the posterior P300 component (mean amplitude of the Pz electrode) was conducted within 250-500ms after stimulus onset. The repeated measures ANOVA consisted of two within-subjects factors; WM load (low, high) and Distractor Type (mismatching, matching).

ANOVA of mean amplitude values within the P300 time window revealed only a significant main effect of WM load *F*(1, 54) = 60.23, *p*< .001, η_p^2 =.53 in that the mean amplitude was more positive under low WM load (*M*= 1.34, *SE*= 0.17) versus high WM load (*M*= .20, *SE*= 0.14). The main effect of Distractor Type was not significant *F*(1, 54) = 1.02, *p*= .32. The interaction between WM load and Distractor Type was not significant *F*(1, 54) = 4.01, *p*= .05, η_p^2 =.07.

3.3.3 Pearson's Correlation Analysis for CFQ and Distractor Interference

The scatterplot (Figure 3.7a) depicts the relationship between the magnitude of distractor interference effect (RTs) and scores on the CFQ Distractibility (CFQ_D) subscale for 55 participants. A significant positive correlation between distractor interference and CFQ_D score ($r(53)= 0.35$, $p< .001$) was found. A follow-up linear regression model was significant in that CFQ_D score explained 12.5% of the variance ($R^2= .13$, $F(1, 53)= 7.55$, $p =.008$). CFQ_D score ($\beta = 1.27$, $p=.01$) can predict the increase in magnitude of distractor interference effect (RTs). These results suggest that the degree of distractor interference in the current paradigm can be predicted by the self-report measure of distractibility.

Table 3.7
Descriptive Statistics and Correlations for CFQ Factors and Lateralised ERPs (N=55)

Variable	*M*	*SD*	1	2	3	4	5	6	7
1. CFQ Total	48.85	13.01	—						
2. CFQ Forgetfulness	16.87	4.10	**.90****	—					
3. CFQ Distractibility	16.58	4.82	**.88****	**.74****	—				
4. CFQ False Triggering	13.33	5.18	**.87****	**.75****	**.64****	—			
5. N2pc_collapsed^a	-0.31	0.65	−.17	-.25	-.10	-.24	—		
6. Pd_collapsed^a	0.43	0.79	−.19	**−.28***	-.19	-.01	.23	—	
7. SPCN_collapsed^a	-0.03	0.53	**-.28***	**−.36****	-.22	−.23	**.44****	**.53****	—

Note: ^{a} Working Memory Load conditions were summed into a single value.
*p <.05. **p <.01.

In terms of the relationship between the lateralized electrophysiological components and the CFQ scores (Figures 3.7b and 3.7c), a significant negative correlation was found for the Pd component and CFQ_D subscale ($r(53)= -.28$, $p= .04$). Moreover, the CFQ Total ($r(53)= -.28$, *p*= .04) and CFQ_Forgetfulness (*r*(53)= -.36, *p*= .008) were significantly correlated, in a negative direction, with the SPCN component.

Figure 3.7a

The Correlation between CFQ Distractibility Scores and Distractor Interference Effect (Reaction Times) Shown as a Scatter Plot for (*N*=55).

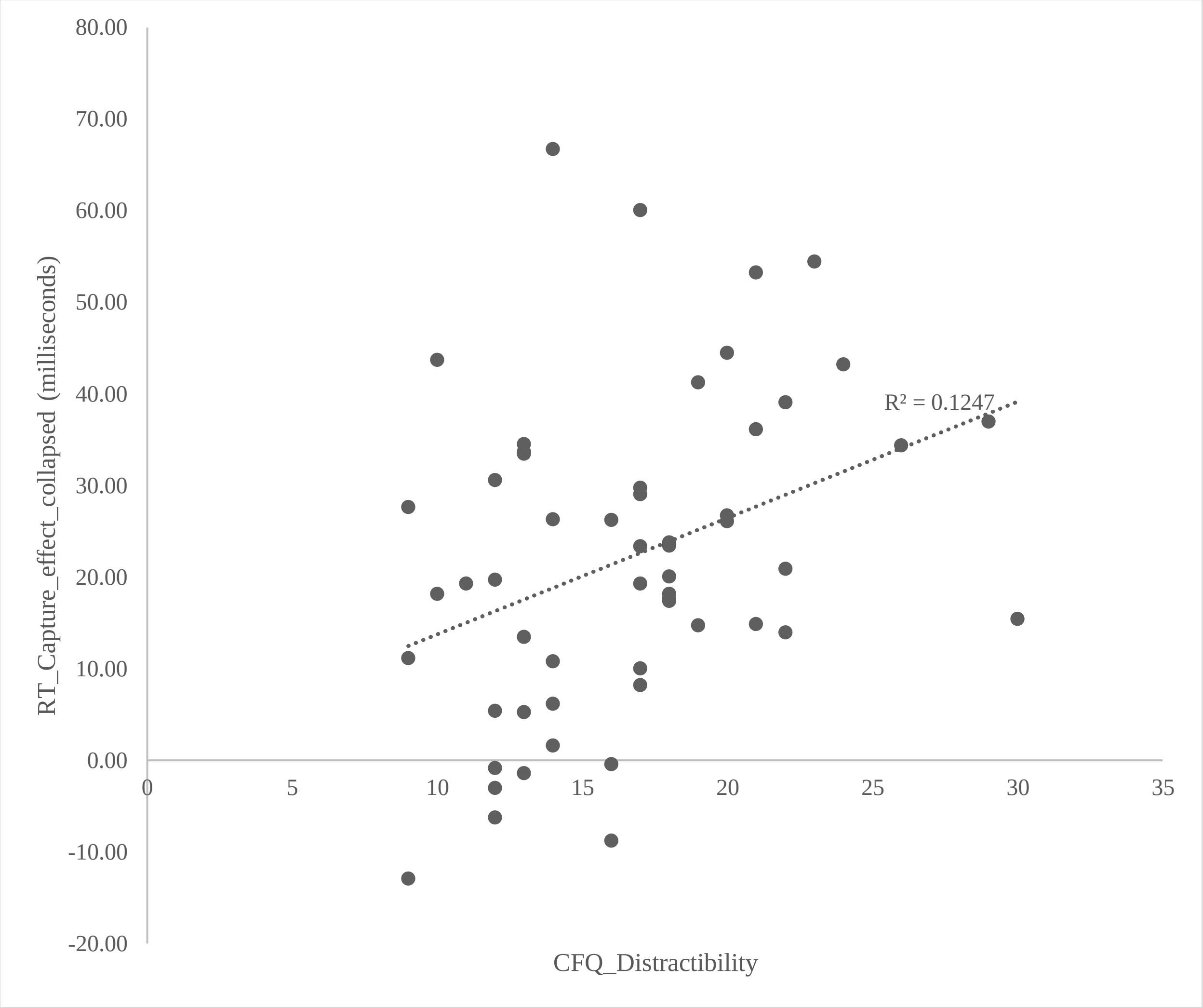


Figure 3.7b

The Correlation between CFQ Distractibility Scores and the SPCN Component Shown as a Scatter Plot for (*N*=55).

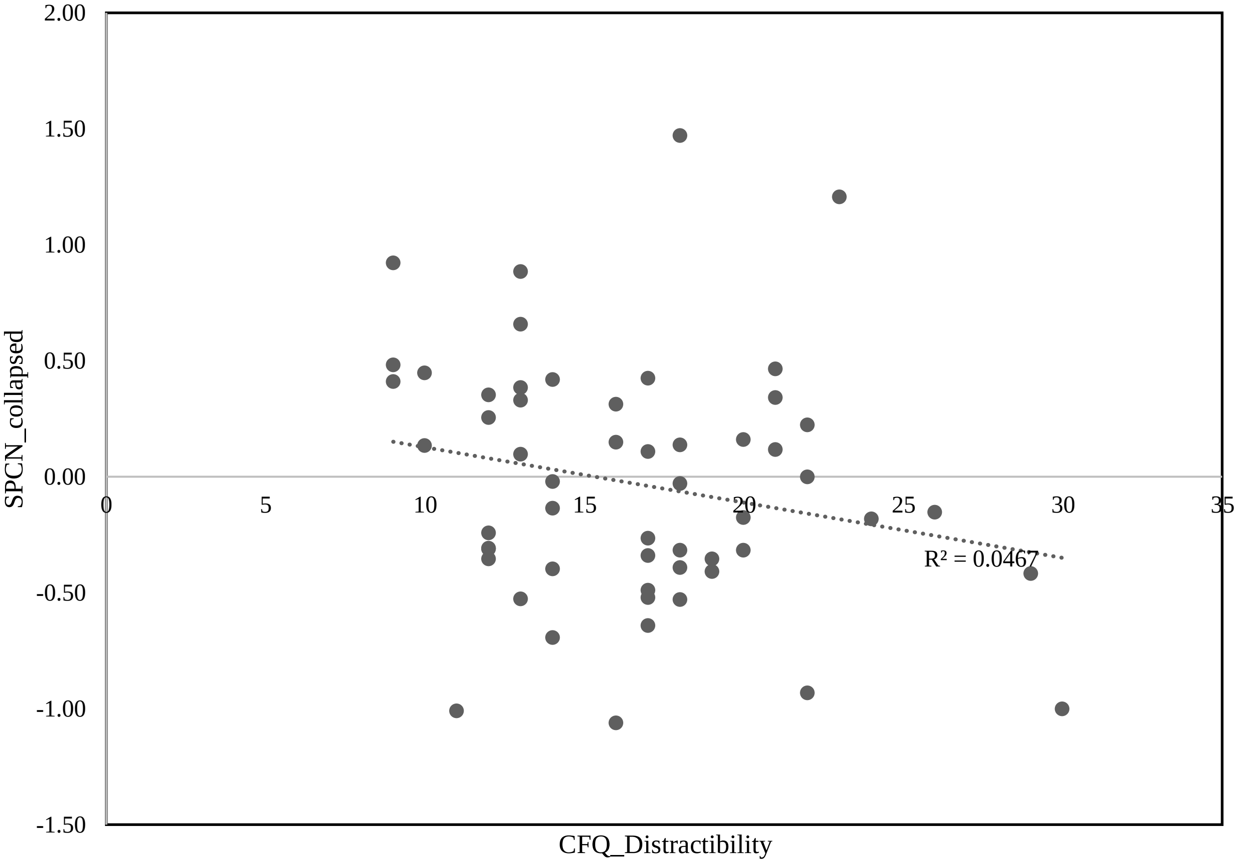
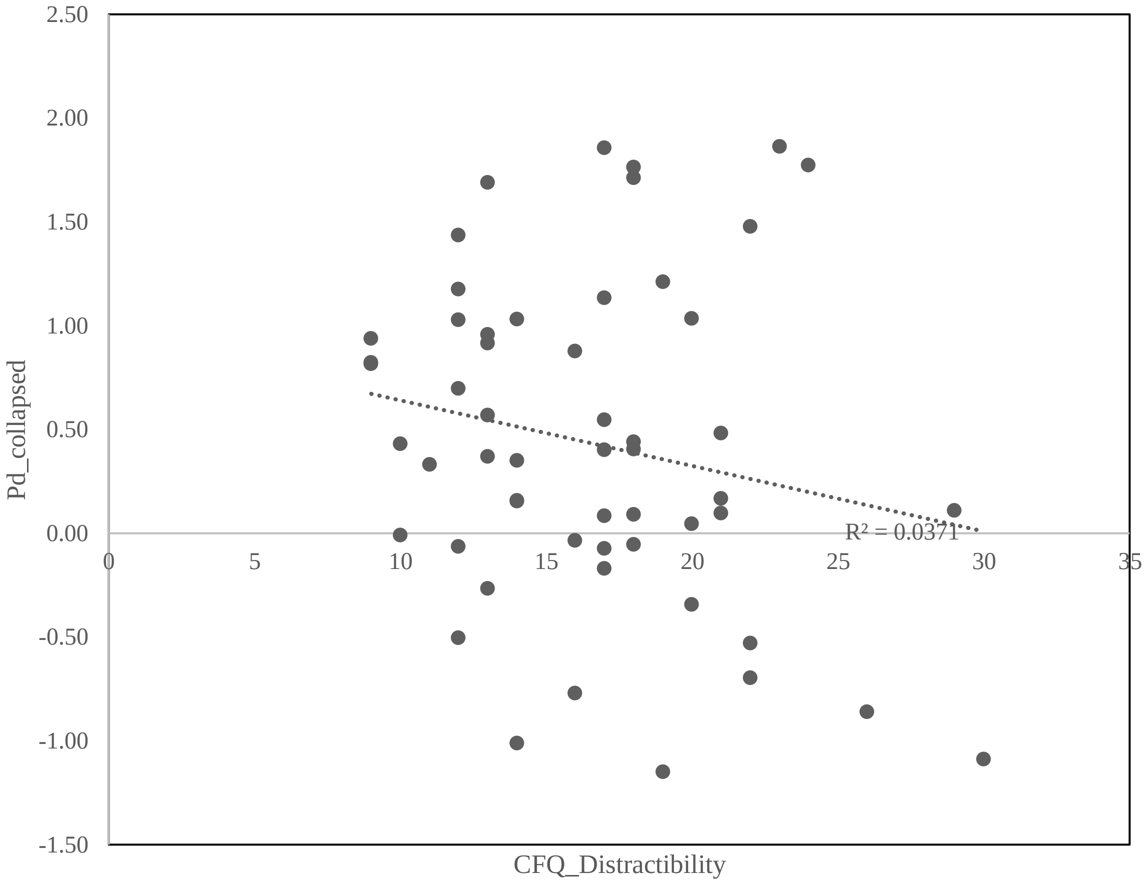


Figure 3.7c

The Correlation between CFQ Distractibility Scores and the Pd Component Shown as a Scatter Plot for (*N*=55).


2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
Pd_collapsed
0
5
10
15
20
25
30
35
R² = 0.0371
CFQ_Distractibility

Summary of Findings

Overall, the behavioural results were inconclusive. It was found that the magnitude of distractor interference was less under low WM load for RTs. In contrast, there was a greater distractor interference effect under high WM load for error rates. This is unsurprising given that behavioural measures reflect a summation of multiple cognitive processes. The majority of the electrophysiological data provides clear support in favour of the TEDTOFF theory in that an individual's susceptibility to a distractor stimulus was greater under low WM load versus high WM load. It was found that distractors captured attention to a greater extent as indexed by a greater N2pc: enhancement of processing a salient pop-out, when participants held less items in WM. There was also less active suppression of the singleton distractor as indexed by a smaller Pd amplitude under low WM load. The SPCN was more negative under low WM load which has been interpreted as stronger sustained maintenance of the distractor which does not support Load Theory. Individuals were not able to prioritise task-relevant information from task-irrelevant information although competition for resources was lower with one item held in WM memory. The EEG results suggest that salient singleton distractors can induce attentional capture even when participants were explicitly told to ignore the array. There was evidence for a reduction in the P300 component with greater WM load, indexing greater distribution of attentional resources across the Updating and Inhibition functions (Scharinger et al., 2015). Early visual components P1 and N1 demonstrated enhanced visual sensory processing when there was less competition for attentional resources, i.e., under low WM load. The anterior P2 reflected the detection of a pop-out stimulus which was stronger in magnitude with low WM load compared to high WM load. The degree of distractor interference effect correlated with the self-reported measure of distractibility, i.e., attention was more likely to be captured by a peripheral distractor for highly distractible participants. The negative correlation between the CFQ Distractibility subscale score and Pd component suggest that low CFQ scores were associated with more active suppression of a singleton distractor. However, the negative correlation between CFQ scores and the SPCN component (reflecting active maintenance process) was less straightforward. It was the reverse of Burra & Kerzel’s (2014) findings in that higher CFQ scores were associated more negative SPCN values (Appendix I).

3.4 Discussion

In summary, the behavioural results provided partial support for Load Theory (Lavie et al., 2004; Forster & Lavie, 2007) in that distractor interference was greater (higher error rates) with increased WM load. The ‘Distractibility’ subscale of the CFQ significantly predicted the increase in magnitude of distractor interference effect for RTs. These results suggest that the degree of distractor interference in the current paradigm can be predicted by the self-report measure of distractibility in everyday life. The decreased distractor processing effects for RTs and especially the electrophysiological results provided empirical support for the TEDTOFF theory (Sörqvist & Rönnberg, 2014). In particular, there was greater early visual processing (P1 and N1), more attentional capture (N2pc), increased detection of pop-out stimuli (anterior P2), reduced active suppression (Pd) and lowered demands on visual WM maintenance (SPCN) induced by peripheral distractors under low WM load. This effect was under conditions where targets and distractors shared the same features as opposed to intermodal task-based studies (Sörqvist et al., 2016). The midline P300 results suggest that attention was more distributed amongst the Updating and Inhibition functions, under high WM load, thus decreased amplitude was observed (Scharinger et al., 2015).

The behavioural results of the current study were inconclusive because different conclusions could be drawn depending on the measure of interest, i.e. greater distractor interference effects for error rates in favour of Load Theory (Lavie et al., 2004) or reduced distractor interference effects for RTs in support of the TEDTOFF theory (Sörqvist & Rönnberg, 2014), under high WM load. For overall mean RTs, responses were significantly faster for matching distractors relative to mismatching distractors. This supports previous studies which have found memory-based attentional capture (Downing & Dodds, 2004; Soto et al., 2005; Woodman & Luck, 2007; Han & Kim, 2009; Kim & Cho, 2016). Improved RT performance in the current study could be due to participants utilizing attentional refreshing of their WM template representation via the matching distractor (Berryhill et al., 2011). Secondly, it could be that salient mismatching (i.e. task-irrelevant) distractors were not successfully ignored, as RTs were longer in this condition (Theeuwes, 2010). Thus, a limitation would be that there was no equivalent control pop-out condition with a pop-out item which was not part of the current task-set. If the anterior P2 component indexes detection of a specific pop-out feature (i.e. colour/shape) then it can be inferred that participants were more likely to engage with the singleton's feature under low WM load (Fuggetta & Duke, 2017). However, future research is warranted for improving the distractor type manipulation by including a neutral pop-out item or varying chromaticity of colours to reduce the probability of engaging in strategic responses. As it currently stands, there is no study specific to selective attention and WM load which has used obscure colours.

The pattern for error rates may be more sensitive to the effects of priming, especially under high WM load. For instance, a distractor item congruent with the WM template may induce a positive PoP effect (reinforcement of at least one stored item) and lead to less errors (Maljkovic & Nakayama, 1994). It was possible that there is a focus of attention for a single item in WM, whereas other representations lie in a dormant or 'accessory' state (Houtkamp & Roelfsema, 2009). According to Carlisle (2019), attentional control may be thought of as a dial flexible to changes in task demands. This idea could also explain the attentional advantage for search-relevant content in WM, as well as the weaker influence of the other item(s) maintained in WM. Given the assumption that there may be a finite amount of resources, for attentional guidance, each object in the high WM load condition would not receive sufficient resources which weakens the guidance effect of WM items (Zhang et al., 2011). If participants were to recode WM items verbally, the guidance of verbal memory is weaker than visual memory (Olivers et al., 2006). It is also plausible that increased WM updating load has impeded inhibitory control (Lavie et al., 2004). Under low WM load, the decision is more straightforward because suppressing a congruent pop-out facilitates the accessibility of a remembered item and benefits task performance. This can be likened to thought suppression experiments whereby instructions to suppress have acted as a reminder for the unwanted thought (Wenzlaff & Wegner, 2000). The load manipulation was successful as evidenced by the significant main effect of WM load for RTs and error rates, i.e. both were increased when more items were maintained in WM. However, previously published studies on the effect of WM load and visual attention have accrued inconsistent findings (Lavie et al., 2004; Sörqvist & Rönnberg, 2014).

Findings from Scharinger and colleagues (2015) who have previously investigated the effects on inhibitory control by increasing ‘WM updating load’ can help to explain the behavioural results from the current study. In terms of RTs, the researchers also found such measures to be sensitive to inhibitory demands, whereby response times were slower for incongruent versus congruent trials. However, the flanker interference effect was in support of the TEDTOFF theory given that the congruency effect decreased with greater WM updating load, which was mirrored in the current study’s distractor interference effect. Similarly, the Updating and Inhibition EF were manipulated within a single task as opposed to dual-task conditions in Load Theory studies. The current study was similar in that the target items in the updating task were identical to the objects in the inhibition task and within the same domain (i.e. visual). In order for lateralized presentations to work, eye movements were minimized in the current study, but it may be informative to include other physiological measures such as pupil dilation, which appears sensitive to inhibitory control demands (Laeng et al., 2011; Scharinger et al., 2015). Shielding from distractor interference findings may be more robust in n-back studies (Pratt et al., 2011; Kim et al., 2017) and cross-modality manipulations (Sörqvist & Marsh, 2015; Simon et al., 2016). Scharinger and colleagues (2017) have posited that n-back may contain dual-task characteristics. The P300 findings replicated that of Scharinger and colleagues' study (2015) in that the significant decrease in amplitude was the result of attention being distributed among updating and inhibition functions. This can be corroborated by the significant increase in error rates under high WM load.

Moreover, the present study's EEG results have not provided direct electrophysiological support for Load Theory's WM load predictions (Lavie et al., 2004) in that the extent to which an individual's attention was captured by distracting stimuli was greater under low WM load (more negative N2pc mean amplitude). The author posits that high WM load has reduced the influence of salient distractors via focal-task engagement, as there was greater active suppression indexed by a greater Pd amplitude (Sörqvist & Marsh, 2015; Feldmann-Wüstefeld & Vogel, 2019). There was support for bottom-up influences on attentional capture, as the N2pc was comparable for the pop-out conditions and suggested that the salience of a singleton distractor overrode task relevance, i.e., no main effect of distractor type. Although Carlisle and Woodman (2013) found goal-dependent influence on N2pc magnitude such that task-relevant stimuli created a larger N2pc, the input must be salient enough to detect any attentional biases. The distractor or target singleton would only appear at four possible locations and was randomised in the current study to minimise the maintenance of spatial information which was not relevant to the task. Whilst the current study has examined visual WM load, others have examined the nature of spatial WM and how the N2pc component is affected by this (reviewed by Couperus et al., 2021). Couperus and colleagues (2021) noted that spatial WM ability predicted better visual search accuracy as well as increased N2pc amplitudes.

It was counterintuitive that the SPCN was less negative under high WM load as the component's magnitude should index the amount of items held in WM (Ikkai et al., 2010; Luria et al., 2016). However, the reduction in amplitude may reflect a weakened sustained maintenance process of more than one item in WM as it reaches capacity (Vogel & Machizawa, 2004) or transference to a long-term memory store (Berggren & Eimer, 2018). Another possibility for a reduced SPCN amplitude could be that the four distinct items (high WM load) were grouped, thus reducing the neural requirements in WM (Peterson et al., 2015). The current experimental design cannot disentangle the influence of WM load from the amount of attentional resources allocated for multiple items (Salahub et al., 2019). Alternatively, the actual encoding of the initial WM template was not strong to begin with, given that more errors were made overall in the high WM load condition regardless of greater active suppression (Pd). Whilst the current SPCN as well as Pd results appear to support the TEDTOFF theory, it should be acknowledged that EEG activity can have a broad range of physiological variability across individuals and even fluctuate on a trial-by-trial basis (Makeig & Onton, 2011). One reason why the CFQ modulations on the N2pc were absent could be due to discrepancy in the number of factor loadings chosen (four factors in Burra & Kerzel, 2014). Performance on lab measures of EF do not consistently relate to scores on questionnaires (e.g., Eisenberg et al., 2019). Other researchers have posited the existence of an extended Pd component which overlaps with the time window of the SPCN (Bretherton et al., 2017). Follow-up studies should consider this idea if the main research question is interested in cognitive processes occurring later in the information processing stream.

The WM load-induced effects on the bilateral N1 component to the distractor in that the N1 reduced with high WM load (Rose et al., 2005; Berggren & Eimer, 2018). The N1 and P1 components reflect early visual processing, and both were modulated by the amount of contents in WM (i.e., load) rather than the type of distractor (i.e., congruency). An explanation for the reduction in both N1 and P1 amplitudes was the competition for attentional resources between the salient distractor and maintenance of the WM contents (Berggren & Eimer, 2018). Thus, the modulation of attention represents a trade-off between external and internal sources of attention (Chun et al., 2011). The current study controlled for perceptual load in that there was a significant overlap between the S2 and S3 array (i.e., isoluminant shapes and colours) similar to previous research (Scharinger et al., 2015; Fuggetta & Duke, 2017). Given that WM load and perceptual load are closely entangled constructs, perceptual load has been offered as an explanation for inconsistent findings (e.g., Konstantinou et al., 2014). Konstantinou and colleagues (2014) have referred to different types of WM load such that visual maintenance load in WM operated in a similar way to perceptual load. Once perceptual capacity has been reached, there is also reduced processing of distractors. Similar to Sreenivasan & Jha (2007), the P1 component did not differ as a function of congruency (type of distractor), which implies no significant differences in spatial processing across the WM load conditions.

The theoretical discussion surrounding Load Theory's WM load effects is incomplete without the consideration of Dilution Theory (Tsal & Benoni, 2010). In the current experiment, the dilution interpretation remains plausible, as the additional stimuli held in WM were perceptually similar to both distractor and target. In line with Roper & Vecera (2013), there are two possible mechanisms of dilution at play. Firstly, there is perceptual dilution, in that the additional items have diluted the representation (via competition of resources) of the distractor before it enters memory. Secondly, there may be a mechanism of dilution within visual WM. Weaker attentional distractor interference effect was found under high WM load as indexed by the reduced (more positive) N2pc waveform. In light of the other ERP results, especially the Pd component, there was a clear indication of greater active suppression of a salient pop-out distractor when maintaining 4 items versus 1 item. This is in accordance with the TEDTOFF theory hypothesising a “shielding” process against distraction in the high WM load condition (Sörqvist & Marsh, 2015). Benoni (2018) proposes a shift from the conventional bottom-up and top-down dichotomy of attention to a *relevance spectrum* to describe different types of attentional deployment. The advantage for this revised taxonomy allows the classification of all instances of effects that may have fallen in between categories (Benoni & Ressler, 2020). Moreover, the view that attending to salient task “irrelevant” items can be viewed not as limitations but as the efficiency of the attentional system.

Related EEG studies have delved into effective connectivity analysis (Kim et al., 2017) and examined frequency band power values (Scharinger et al., 2017). Future investigations could consider the causal role of updating-EF-specific load in distraction suppression by incorporating transcranial magnetic stimulation (TMS) into the experimental design (Thut & Miniussi, 2009). For example, it has been found that the right posterior parietal cortex (rPPC) and right dorsolateral prefrontal cortex (rDLPFC) were both involved in top-down control during a spatial negative priming paradigm (Kehrer et al., 2009; 2015). There is evidence for right-hemispheric dominance in attentional control, specifically in studies documenting effects of stimulating the rPPC and right frontal eye field (Duecker & Sack, 2015). It may be of interest to adapt the current study to test children (Shimi et al., 2015), clinical populations who struggle with attentional engagement (Reilly et al., 2017) or the general population exhibiting traits related to schizotypy (Fuggetta et al., 2015). Other factors to consider include the positive effects of practice (Fuggetta & Duke, 2017) and value-driven attentional capture (Anderson & Yantis, 2013).

To conclude, there was partial support for Load Theory (Lavie et al., 2004) demonstrated by an increase in distractor interference effect for the error rate data. The electrophysiological data showed that individuals were more susceptible to attentional capture from peripheral distractors (more negative N2pc amplitude) when fewer items were maintained in WM, supporting the TEDTOFF theory (Sörqvist & Rönnberg, 2014) and Dilution Theory (Tsal & Benoni, 2010). Additionally, there was evidence for more suppression and decreased sustained processing of distractors with increased WM load, as indexed by the Pd component. Moreover, the novel paradigm specifically targeting the updating and inhibition EF had replicated WM load effects for the P300 component. In the next chapter of this thesis, a TMS-EEG combined protocol was used to consolidate the role of the rPPC and rDLPFC in visual attention by applying stimulation during the presentation of a distractor array to examine either facilitatory or inhibitory effects. The advantage of combining EEG and TMS is the potential to provide empirical evidence regarding which area is affected by TMS (i.e., the stimulated area or areas connected to the stimulated site), if stimulation effects are immediate or delayed in time and how the effects of TMS correlate with behaviour (Miniussi & Thut, 2010).

Chapter 4: The Causal Role of rDLPFC and rPPC in Working Memory and Selective Attention.

4.1 Introduction

Experiments 1 and 2 (from Chapters 2 and 3 respectively) were designed to empirically test the WM load predictions from the Load Theory of Attention and Cognitive Control (LT; Lavie et al., 2004). In Experiment 1, there was partial support for LT and capacity load predictions (e.g., Zhang & Luck, 2015) in that there was a significant increase in distractor interference, as participants were making more errors with increased WM load. However, the increase plateaued as WM load approached its maximal capacity of 3-4 items, which cannot be fully accounted for by Konstantinou and colleagues' (2014) distinction between different roles of WM load in distractor suppression. Additionally, the behavioural data was inconclusive in Experiment 2, with the error rates in favour of LT (Lavie et al., 2004) whilst RTs were in support of the TEDTOFF theory (Sörqvist & Rönnberg, 2014). This was consistent with previous research demonstrating mixed results and minimal replication of LT predictions (He & Chen, 2010; Wei et al., 2013; Yao et al., 2020). The inclusion of neurophysiological measures demonstrated clearer evidence that individuals were more likely to allocate attention to peripheral distracting stimuli under conditions of low WM load. Established neural correlates of attention such as the N2pc component and Pd component (Eimer, 1996; Hickey et al., 2009) indicated that the extent of distractor interference was greater when the Updating component of EF load was low, consistent with the TEDTOFF theory. However, the low spatial resolution afforded by electroencephalography (EEG) cannot establish the causal relations between neural regions involved in selective attention, WM load and neural correlates. A combined repetitive transcranial magnetic stimulation (rTMS) and EEG procedure was used in the present study by assessing the effect of TMS on event-related potentials, i.e., causal interactions between anatomically and functionally connected regions (Thut et al., 2003; Fuggetta et al., 2006).

The dorsal fronto-parietal attention network has been investigated in relation to selective attention and WM (Corbetta & Shulman, 2002), thus the potential TMS targets were the dorsolateral prefrontal cortex (DLPFC) and posterior parietal cortex (PPC). The PFC has been hypothesized to function as an "executive controller" akin to Baddeley's (2003) model of WM, and this brain region acts as a "dynamic filter" which selectively gates and controls information processing in more posterior cortical regions (Shimamura, 2000). On the other hand, the PPC has been associated with a variety of cognitive operations, as it is distributed across visual, auditory and tactile cortices (see Berryhill, 2012 for a review). Frontal and parietal brain regions have been implicated in attentional control for visuo-spatial information (Hopfinger et al., 2000; Chambers & Mattingley, 2005; Silver et al., 2005; Chiu & Yantis, 2009; Greenberg et al., 2010) and visual WM (Todd & Marois, 2004; Postle et al., 2006; Xu & Chun, 2006; Hamidi et al., 2009; Preston et al., 2010; Zanto et al., 2011; Feredoes et al., 2011; Liesefeld et al., 2014). Whilst researchers in favour of Load Theory have posited that high WM load ("cognitive control" load) emulates the effect of frontal lobe damage, these studies have been based on behavioural data (Lavie et al. 2004; Olivers et al., 2006; Konstantinou et al., 2014) and functional imaging data (De Fockert et al., 2001; Yi et al., 2004). An alternative approach would be to non-invasively stimulate underlying neural tissue via electromagnetic induction (Barker et al., 1985) with TMS. This neuroscientific technique can help to establish a causal role for a specific brain region in a cognitive function such as selective attention (Pascual-Leone et al., 2000). The dorsal FPN (Corbetta & Shulman, 2002) has been of particular interest for TMS studies in attentional control targeting the right PPC and right DLPFC (Kehrer et al., 2015; Yan et al., 2016; Wang et al., 2018; 2020; for a review Duecker & Sack, 2015). These studies have generally found adverse effects of TMS (slower response times) when the experimental task involved spatial WM.

Yan and colleagues (2016) demonstrated the role of the rDLPFC and rPPC in top-down and bottom-up biasing of attention (Yan et al., 2016). They administered 2 pulses of 10Hz rTMS with MNI values for the rDLPFC (45, 30, 31) and rPPC (43, -65, 51). In particular, the authors were interested in TMS interference immediately prior to the onset of a visual search array. Both top-down and bottom-up influences on attentional control were examined by disrupting frontal (source of top-down control) and parietal (associated with top-down and bottom-up processes) cortices. As predicted, there were selective effects of the rDLPFC in top-down biasing of attention towards targets amidst distractors in the visual search condition (in agreement with Sandrini et al., 2008). Moreover, rPPC effects were present, indexed by elongated RTs, for the pop-out search (predominantly driven by bottom-up processes) as well as the visual search when the target was presented in the left visual field. Therefore, the rPPC may act as a brain region susceptible to the modulations of top-down and bottom-up signals. In existing rPPC-targeted studies, there was evidence of rPPC involvement in attentional capture effects of salient distractors (Constantinidis, 2005; Mevorach et al. 2006; Hodsoll et al., 2009).

A recent study by Wang and colleagues (2018) targeted the effects of concurrent WM representation maintenance on attentional control during visual search within the FPN. The authors used a 10Hz rTMS protocol of 5 pulses to induce a suppressive effect on cognitive processing by targeting the MNI coordinates for rDLPFC (42, 30, 41) and rPPC (42, -44, 40). Their experimental design emphasized the WM component in which participants would have to remember a colour for a subsequent memory test. In this experiment, administration of TMS to the rDLPFC and the rPPC led to a significant decrease in search RTs only when the item maintained in WM and visual search array fully matched the task goals (i.e., valid trial conditions). An absence of TMS effects on memory test performance was attributed to the short-lasting duration of rTMS. Wang and colleagues (2020) followed up their results with an fMRI-guided TMS experiment and both frontal (rDLPFC and right frontal eye field) and parietal (right superior frontal lobule) regions were activated during top-down visual search. By delivering TMS pulses concurrent with the onset of visual search, the researchers were able to confirm the rDLPFC's involvement in successful maintenance of target representations specific to the difficult non pop-out condition (i.e., distractors were the same colour as the target). Thus, the authors interpreted their results in that easy pop-out searches may be less sensitive to rTMS manipulations, as the task was less cognitively demanding. Other fMRI studies have demonstrated that the rDLPFC is sensitive to changes in WM load (Manoach et al., 2004; Huang et al., 2013). Higher activation of the rDLPFC has been associated with increased WM load. Other regions of interest (ROIs) include the right angular gyrus (Taylor et al., 2011) and frontal eye fields (FEFs) were investigated using a pop-out visual search (O'Shea et al., 2007).

Another study investigated the involvement of the rPPC and rDLPFC in visual spatial attention using a single-pulse TMS protocol (Kehrer et al., 2015). The authors used a single-pulse TMS protocol to investigate the time course of spatial priming with MNI values (42, 30, 41) for the rDLPFC and (42, -44, 40) rPPC. TMS was delivered at five different timepoints (50, 100, 150, 200 and 250 ms). There was a significant effect of TMS only 100ms after the onset of a probe item display in a spatial negative priming (NP) paradigm. There was enhanced positive priming for stimuli presented at a location where a target was previously and reduced negative priming at a previous distractor position. In line with inhibition theory (Tipper, 2001), a decrease in the NP effect due to TMS stimulation at a specific time interval suggested that the top-down driven inhibitory process was effectively disrupted. In a previous related EEG study, Kehrer and colleagues (2009) demonstrated the involvement of fronto-central and parietal activity in relation to cognitive control. The authors found evident differential effects of NP only in the easy task condition, in line with other studies (Gibbons et al., 2006; Kathmann et al., 2006; Ruge & Naumann, 2006).

A study pertinent to the contribution of combining neuroimaging techniques (i.e. TMS and EEG) was conducted by Fuggetta and colleagues (2006). These researchers employed a single-pulse TMS-ERP combined method within the context of visual search. In particular, they found impaired task performance (i.e. delayed RTs) after stimulating the rPPC during a conjunction search (e.g. colour and orientation of a visual object) in comparison to control stimulation. The onset of the N2pc component was delayed after TMS delivery, which was interpreted as disruption of the rPPC's contribution in attentional control. Fuggetta et al. (2006) provided empirical evidence for the role of the rPPC in conjunction search for targets, akin to a previous TMS study (Ashbridge et al., 1997) and EEG studies specific to N2pc and conjunction search (Berggren & Eimer, 2018).

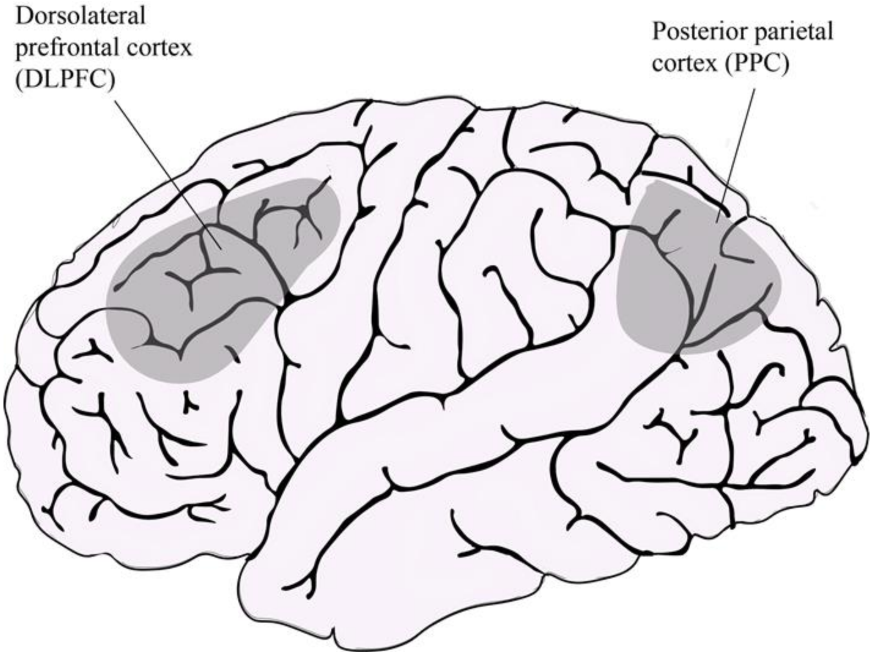
There appears to be a range of similarities and differences in experimental designs adopted by the aforementioned studies. There has been a lot of variability in the types of tasks employed in previous work such as conjunction search (Fuggetta et al., 2006), pop-out search (Wang et al., 2018), conjunction and pop-out visual search (Yan et al., 2016), spatial priming (Kehrer et al., 2015), and delayed recognition WM task (Feredoes et al., 2011). TMS studies which target the rDLPFC and rPPC have either used 5 pulses at search onset (Kehrer et al., 2015; Wang et al., 2018) or 2 pulses before search onset (Yan et al., 2016). In particular, this group of studies found support for the role of the rDLPFC in top-down attentional control and the rPPC in processing of spatial information. On the other hand, TMS-fMRI studies with 3 TMS pulses have found significant effects of the DLPFC in protecting the representation of a target (Feredoes et al., 2011; Zanto et al., 2011; Wang et al., 2020). As for TMS-EEG studies (Ashbridge et al. 1997; Fuggetta et al. 2006), the rPPC has been the ROI and a single-pulse protocol has confirmed its role in conjunction search. The current study is novel in that previous studies have not employed an rTMS-EEG protocol, targeting both the rDLPFC and rPPC, with a modified delayed match-to-sample task (DMTS; Fuggetta & Duke, 2017). An advantage of the modified DMTS task is that specific WM components have been targeted, i.e. Updating and Inhibition functions (Friedman & Miyake, 2017) rather than a general central executive load (Allen et al., 2017).

Study Aims

The first aim of the current study was to further investigate the WM load effects by pitting the predictions from Load Theory (Lavie et al., 2004) against those of TEDTOFF theory (Sörqvist & Rönnberg, 2014). The behavioural data predictions of the current study remain bi-directional such that increased WM load may lead to greater (Lavie & De Fockert, 2005; Lavie, 2010) or reduced (SanMiguel et al., 2008; Sörqvist et al., 2016) distractor interference. The current study extended the methodology of Fuggetta and colleagues (2006) in several ways: manipulating WM load conditions, including rDLPFC as a TMS site of interest, locating TMS sites using neuro-navigation rather than approximating from the P4 electrode position and adopting an rTMS protocol as opposed to single-pulse. The task of choice in the current study was a modified delayed match-to-sample task (similar to Bennett et al., 2014; Fuggetta et al., 2015; 2017). The delineation of memory processes in time, i.e. encoding, maintenance and retrieval, is suitable for a TMS-ERP protocol. The delivery of TMS can be time-locked to the onset of the distractor array (Feredoes et al., 2011) during the retention interval (Wang et al., 2018).

Figure 4.1

Lateral View of Dorsolateral Prefrontal Cortex and Posterior Parietal Cortex.



Given that WM representations are distributed amongst sensory, parietal and prefrontal cortices (Cristophel et al., 2017), it would be appropriate to target across cortices, specifically parietal and prefrontal. The second aim of this chapter was to investigate the causal role of two nodes within the dorsal fronto-parietal network (FPN) in the right hemisphere; the dorsolateral prefrontal cortex (DLPFC) and posterior parietal cortex (PPC). Right-hemispheric effects as observed in TMS studies targeting the dorsal FPN (Chambers et al., 2006; Rushworth & Taylor, 2006; Duecker & Sack, 2015) have been more dominant than those in the left-hemisphere. Thus, the right DLPFC and PPC areas and their causal involvement with regards to WM and selective attention were of primary interest. The MNI values chosen were identical to (Kehrer et al., 2015; Wang et al., 2018). The prediction for the current study was that the delivery of rTMS would disrupt the processing of the distractor array and consequently benefit task performance. However, there are other predictions to consider such as those provided by Wang and colleagues (2018). For instance, disruption to the rDLPFC may eliminate both facilitation (WM item and distractor congruency) and cost (WM item and distractor incongruency) effects if this ROI is responsible for

WM biased effects on visual search. Moreover, if the rPPC is involved in distraction suppression then it is expected that performance is improved by delivering TMS. Increased search time is expected if the rPPC exerts a role in the top–down selection of task-relevant targets surrounded by distractors (Fuggetta et al., 2006; Lane et al., 2011). WM guidance theories (e.g., Zhang et al., 2011) would have two predictions. In conditions where the WM item and distractor are matched, response times should be faster and less errors should be made. For conditions where the WM item and distractor are mismatched, more errors should be made and accompanied by slower response times.

4.2 Method

4.2.1 Participants

The sample size (N=30) for Experiment 3 was *a priori* calculated using G*power 3.1. (Faul et al., 2007) for the repeated measures ANOVA, with an expected medium effect size ($\eta^2 = 0.06$), power of .90, and alpha level of .05. 35 volunteers started the experiment and had given written informed consent. 33 participants (*M* age = 24.88 years, range = 18-39 years, *SD* = 5.04, 23 females, 5 left-handed) were included in the final analyses. One participant was excluded due to technical error and another for a low number of correct trials. All participants had normal or corrected-to-normal vision and reported no use of medication, history of psychiatric or neurological disorders. The inclusion criteria was similar to Experiment 2 with the addition of the TMS screening questionnaire (Appendix C) according to recent guidelines (Rossi et al., 2009) to minimize potential risks to participants. This will involve the use of a research protocol that falls within widely agreed safety limits, and a conservative approach with the TMS screening questionnaire. The University of Roehampton ethics committee granted ethical approval for this study. Participants were mainly recruited from the University of Roehampton and the general population via online advertisement and personal communication. Participants were reimbursed £10 gift vouchers per hour of participation. Full debriefing about the purpose of the study was given to participants at the end of each session.

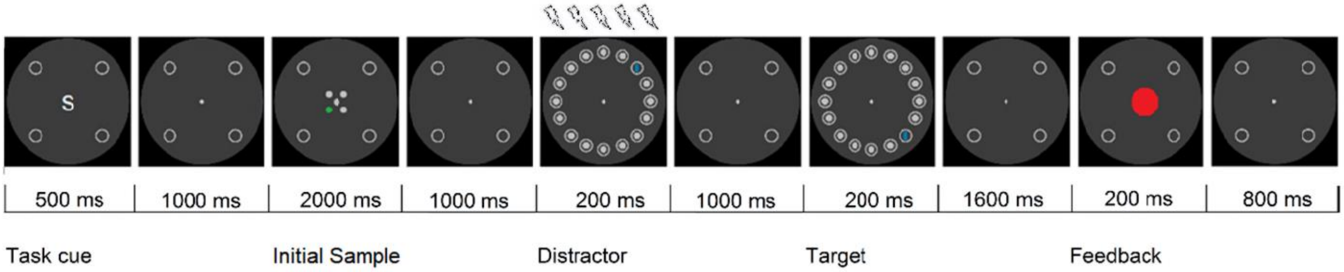
4.2.2 Materials and Procedure

Visual task The DMTS task used was similar to Experiment 2 with a few minor adjustments (Figure 4.1). Participants completed eight blocks of 64 trials (Total= 512) and were allowed to pause between blocks whilst the TMS coil was changed. The sequence of events was exactly the same as Experiment 2 except for the exclusion of the neutral distractor condition. The RGB values can referred to in Appendix F(iii).

Participants were naïve to the aims of the experiment. All participants were tested individually in a dimly lit room and completed the computer task for approximately 1 hour. The placement of EEG electrodes and TMS neuro-navigation set-up took approximately 1 hour and 30 minutes. Participants were instructed to fixate on the screen throughout trials. They were told to respond as quickly and accurately as possible using a button response box. Participants completed 32 practice trials to familiarize themselves with the task before the main experimental phase. The practice phase was repeated until the accuracy reached a threshold of at least 85%. Behavioral performance (response times and performance accuracy) was recorded alongside EEG recording and delivery of TMS pulses. To reduce head motion, a chin-rest was used for each participant and the fixed viewing distance was 71 cm. An in-house experiment generator software programmed with Lazarus (https://www.lazarus-ide.org/) was used to present the experiment on a 24" LCD monitor (AOC G2460PG G-SYNC) with 1 ms response time, a resolution of 1920 x 1080 pixels and a refresh rate of 100 Hz.

Figure 4.2

Example of sequence of events of a trial of the visual task varying the *updating* EF load.



Note. This trial is an example of the shape task, low WM load and mismatching condition. This is because the task cue is "S", the informative cue has one shape to be rehearsed in WM and the distractor is different from the target shape. For illustrative purposes, the lightning bolts represent five TMS pulses delivered during distractor onset in the experiment.

4.2.3 EEG Data Acquisition

EEG signals were recorded from a 64-channel Neuroscan Synamps system (Neurosoft Inc., USA) using CURRY 8 software (Compumedics USA Inc) with a sampling rate of 10,000 Hz which was reduced to 1,000 Hz during signal analysis. A Braincap with passive TMS-compatible "multitrodes" (Brain Products GmbH) following the extended 10/20 system. Flat electrodes were chosen as they enabled the TMS coil to be placed close to the scalp. Horizontal electrooculograms were recorded via electrodes placed 1cm from the outer canthi of both eyes. Vertical electrooculograms and blinks were recorded using two electrodes; one placed above and one below the left eye. There were an additional two electrodes placed on each earlobe. The FCz electrode was used as an online reference electrode for EEG recordings. After artefact removal, the EEG waveforms were re-referenced offline to the Common Average Reference (CAR). Electrode impedance was kept below 5 kΩ.

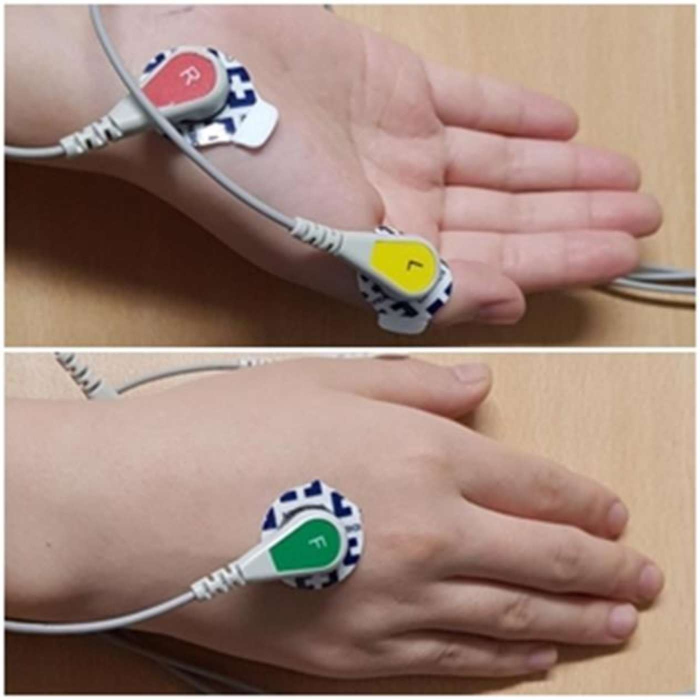
The pipeline used for artifact removal (especially those induced by TMS) can be found in Appendix G. This process required the TESA toolbox (Rogasch et al., 2017) within MATLAB's EEGLAB toolbox (Delorme & Makeig, 2004). This pipeline included the interpolation of bad electrode channels and independent components analysis. Brain Vision Analyzer 2 (Brain Products GmbH) was used to create grand averages. The electrophysiological data will not be presented as the TMS artefact removal process was unsuccessful.

4.2.4 rTMS Protocol/Procedure

Trains of 500ms 10Hz rTMS (i.e., 5 pulses) were delivered using an EEG compatible figure-of-eight coil (70-mm outer diameter) with a Magstim Super Rapid^2 stimulator (Whitland, UK). The coil was placed at a 45° tangent to the scalp with the handle pointed superiorly. The TMS coordinates over right DLPFC and right PPC were selected based on the Montreal Neurological Institute (MNI) values reported in two previous studies (Kehrer et al., 2015; Wang et al., 2018). The MNI values for the rDLPFC (42, 30, 41) and rPPC (42, -44, 40) and converted to Tailarach space for the frameless neuro-navigation system (*41, 32, 39*; *42, -41, 38*). The rDLPFC and rPPC sites were localised using a TMS-magnetic resonance imaging coregistration system (SofTaxic, Italy, http://www.emsmedical.net/). Location estimates were based on an MRI-constructed stereotaxic template and digitized skull landmarks (nasion, inion, and two preauricular points) akin to (Rizzo et al., 2007; Capotosto et al., 2009). The short rTMS trains were delivered during the presentation of distractor array i.e.., the onset of the visual search, as in (Fuggetta et al., 2008; Wang et al., 2018). The average intensity was 63% of maximum stimulator output and the average values for each site were rDLPFC (89%), rPPC (92%) and Vertex (92%) of RMT. rDLPFC stimulation was lowered in comparison to the other sites to reduce participant discomfort, eye blinks and muscle twitches. The location of Vertex (Cz on the 10-20 system) was determined as the midpoint between the Nasion and Inion and equidistant from the right and left ear of each individual. The Cz site was used as a control site because it minimises effects on behaviour whilst inducing auditory and somatosensory activations equivalent to the 'real' TMS conditions (Sandrini et al., 2011; Jung et al., 2016). A No-TMS condition was also included. Pulses of stimulation were delivered during the practice phase trials (N= 48) in order to familiarise participants with the sensations of TMS. Overall, each participant received 1920 TMS pulses during the experiment which was in accordance with published safety guidelines for TMS stimulation (Wassermann, 1998; Rossi et al., 2009). The rTMS was tolerated well by participants and no adverse effects were reported.

***Figure* 4.2**

EMG electrode placement.



Note. Yellow electrode on lateral face of thumb; red electrode on belly of the thumb (Abductor Pollicis Brevis) and green electrode on the back of hand for grounding.

Prior to rTMS, electromyographic (EMG) electrodes were placed on the surface of each participant's right hand as illustrated in Figure 4.2, to establish the resting motor threshold (RMT). Multiple electrodes were needed because EMG recordings reflect the potential difference in voltage between two separate electrodes. The RMT is considered to be the minimum intensity of TMS stimulation to generate a motor-evoked potential (MEP) of at least 50 μV peak-to-peak in five out of ten consecutive trials. Both the MEP and RMT are indirect measures of cortico-spinal excitability (Rothwell, 1997; Rothwell et al., 1999). The participant wore a swimming cap with the location of vertex marked. The primary motor cortex was located by moving the TMS coil in 0.5-1 cm increments on the scalp leftward away from the vertex, towards the location of the motor "hotspot" (Conforto et al., 2004). The experimenter navigated the TMS coil which delivered the stimulation at a high intensity of maximum stimulator output to begin with, whilst counting the number of times the EMG response exceeded 50 μV. A second experimenter observed for muscle twitches specifically in the right thumb. When both experimenters were in agreement of 5 visible occurrences, the TMS intensity was reduced in increments of 2% until completion (lowest intensity which still elicited muscle movement). The primary criterion (i.e., EMG) was used to determine 100% of RMT in response to a single TMS pulse. Visual inspection was a secondary method used to ascertain that the intensity of stimulation was minimising a motor response.

4.2.5 Experimental Design

The independent variables were WM load (one and four items to rehearse in WM), TMS site (rDLPFC, rPPC, Vertex, No TMS) and Distractor type (incongruent and congruent to initial sample). The dependent variables consisted of behavioural measures; reaction times (milliseconds) and error rates (%) as well as electrophysiological data (electroencephalography). The magnitude of distractor interference effect of the initial sample (S1) on the distractor (S2) was computed by subtracting the task performance between the following two conditions: Distractor Type Mismatching minus Distractor Type Matching. Only the shape task was used to adhere to number of trials within the safety limits of TMS administration. Distractor interference was indexed through the reaction times to the target as a function of the distractor's congruency with the initial sample. Distractor interference is inferred from the slowing down of reaction times in the presence of incongruent distractors as compared with congruent or neutral distractors. An rTMS protocol induces after-effects which can persist beyond the stimulation period (Sandrini et al., 2011). The TMS sites of interest were targeted specifically to disrupt the top-down control processes demonstrated in similar studies (Kehrer et al., 2015; Wang et al. 2018).

4.3 Results

In all ANOVAs, Greenhouse-Geisser epsilon adjustments were applied for cases of non-sphericity. As for post-hoc paired t-tests, multiple comparisons were Bonferroni corrected. A two-tailed hypothesis was used therefore the alpha level was 0.05. All statistical analyses were performed using Statistical Package for the Social Sciences Statistics (SPSS Version 26, IBM).

4.3.1 Behavioural Data

Only correct responses and RTs longer than 150 ms were analysed with 2.23% of trials removed from analysis. Responses longer than 1800 ms were logged by the system as omissions. RTs (milliseconds) and percentage error rates of correct responses were analyzed with a 3-way repeated measures ANOVA. The within-subjects factors were WM load set-size (1 versus 4 items), Distractor Type (different from initial sample, same as initial sample) and TMS site (rDLPFC, rPPC, Vertex and No TMS).

Table 4.1
ANOVA Results for Mean RTs in the DMTS Task.

Source	*Df*	*F*	Sig.	Partial Eta Squared
Site	**2.48, 79.38**	**5.79**	**.002**	**.02**
WML	**1, 32**	**150.98**	**<.001**	**.83**
DT	**1, 32**	**30.63**	**<.001**	**.49**
Site * WML	2.62, 84.01	1.25	.30	.04
Site * DT	2.82, 90.13	.22	.87	.01
WML * DT	1, 32	2.10	.16	.06
Site * WML * DT	2.49, 79.68	.81	.47	.03

Note: Site= Site of TMS, WML= Working Memory Load, DT= Distractor Type and df= degrees of freedom. Significant main effects and interactions are bolded.

Reaction Times

ANOVA of RTs revealed a significant main effect of WM Load *F*(1, 32) =150.98, *p*<.001, ηp2 =.83 showing that participants were slower to respond to the high WM load condition (*M*=759.02, *SE*=26.94) than the low WM load condition (*M*=618.26, *SE*=22.86). A main effect of TMS Site *F*(2.48, 79.38) =5.79, *p*=.002, ηp2 =.02 (Figure 4.3) revealed that participants were slowest in response to no TMS stimulation (*M*=709.35, *SE*=23.71), Vertex stimulation (*M*=683.23, *SE*=25.28), rPPC stimulation (*M*=686.37, *SE*=25.55), and quickest to respond with rDLPFC stimulation (*M*=675.61, *SE*=24.91). Pairwise comparisons revealed a significant difference between the no TMS stimulation and rDLPFC stimulation conditions (*MD*= 33.74, *SE*= 10, *p*=.01) whereas other pairwise comparisons were not significant (*p*> .05). A significant main effect of Distractor Type *F*(1, 32) =30.63, *p*<.001, ηp2 =.49 demonstrated that participants were slower in response to the mismatching distractors (*M*=697.68, *SE*=24.49) than matching distractors (*M*=679.60, *SE*=24.25). All other comparisons were not significant (*ps*> .05).

Figure 4.3

Mean RTs by TMS Site of Stimulation.

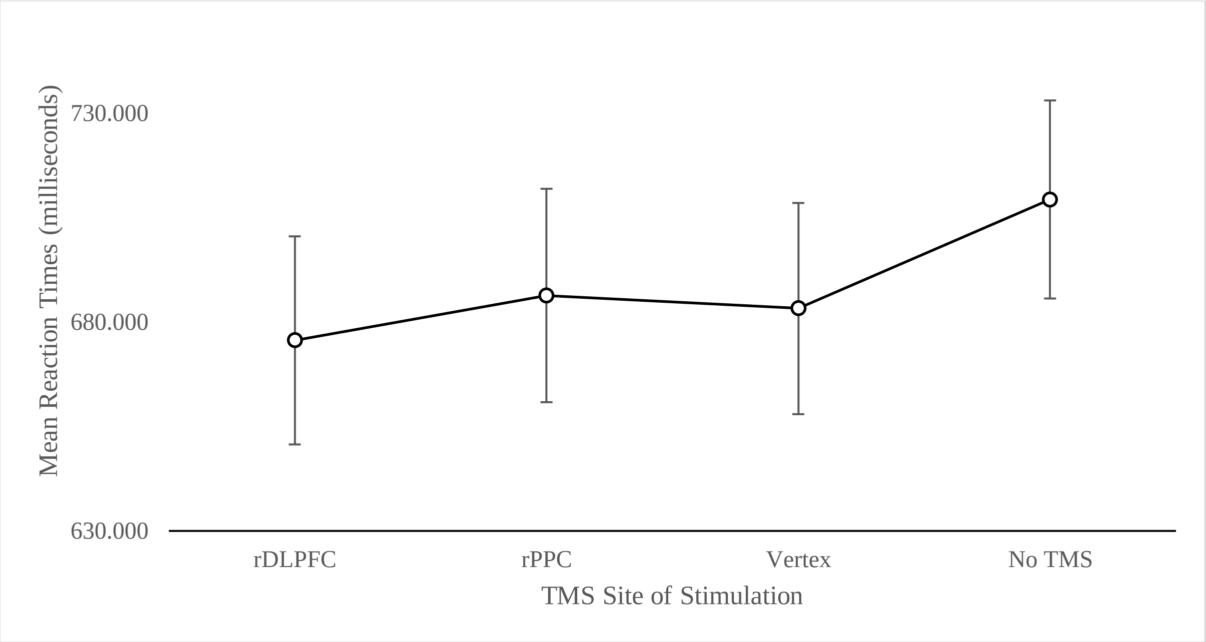


Table 4.2

ANOVA Results for Mean Error Rates in the DMTS Task.

Source	*Df*	*F*	Sig.	Partial Eta Squared
Site	3, 96	2.32	.08	.07
WML	**1, 32**	**228.08**	**<.001**	**.88**

Source	*Df*	*F*	Sig.	Partial Eta Squared
DT	**1, 32**	**5.24**	**.03**	**.14**
Site * WML	3, 96	1.82	.15	.05
Site * DT	3, 96	.46	.71	.01
WML * DT	**1, 32**	**4.22**	**.048**	**.12**
Site * WML * DT	3, 96	2.25	.09	.07

Note: Site= Site of TMS, WML= Working Memory Load, DT= Distractor Type and df= degrees of freedom. Significant main effects and interactions are bolded. The WML * DT interaction was marginally significant.

Error Rates

ANOVA of error rates revealed a significant main effect of WM load *F*(1, 32) =228.08, *p*<.001, ηp2 =.88 showing that participants were least accurate in responding with high WM load (*M*=24.73, *SE*= 1.45) versus low WM load (*M*= 6.64, *SE*=.72). A main effect of Distractor Type *F*(1, 32) =5.24, *p*= .03, ηp2 =.14 revealed that participants were less accurate at responding to distractors which mismatched (*M*=16.56, *SE*= 1.10) than distractors which matched (*M*= 14.81, *SE*=1.00) the initial sample. There was a marginally significant two-way interaction between WM load and Distractor Type *F*(1, 32) =4.22, *p*= .048, ηp2 =.12. Pairwise comparisons revealed a significant difference between the mismatching and matching conditions, under high WM load (*MD*= 3.25, *SE*= 1.36, *p*=.02) but not for low WM load (*MD*= 0.26, *SE*= .62, *p*=.68). All other comparisons were not significant (*ps*> .05).

Distractor Interference Effect

The magnitude of distractor interference effect of RTs and error rates was computed as the difference between conditions: Distractor Type Mismatching minus Distractor Type Matching. A

2-way repeated measures ANOVA with the within-subjects factors; TMS site (rDLPFC, rPPC, Vertex, No TMS) and WM load (low, high) was conducted.

ANOVA of RTs revealed no significant main effect of TMS Site *F*(3, 96) =.22, *p*=.88, WM load *F*(1, 32) =2.10, *p*=.16, nor a 2-way interaction of TMS Site x WM load *F*(3, 96) =.81, *p*=.49. ANOVA of error rates revealed no significant main effect of TMS Site *F*(3, 96) =.46, *p*=.71. There was a marginal significant main effect of WM load *F*(1, 32) =4.22, *p*=.048, ηp2 =.12 showing that the distractor compatibility effect was less under low load (*M*=.26, *SE*=0.62) than high load (*M*=3.25, *SE*=1.36). The 2-way interaction of TMS Site x WM load *F*(3, 96) =2.25, *p*=.09 was not significant.

The electrophysiological data was not analysed as the TMS artefact removal process was unsuccessful. Please refer to Appendix J which shows the harsh removal of ERP signals, at distractor onset, of all the TMS stimulation conditions (in comparison to a No TMS condition). The No TMS condition was not of interest to the primary aim of this chapter which was to observe the effects of TMS application, during distractor onset, on the behavioural and electrophysiological data. Although the TMS protocol did not affect the magnitude of distractor compatibility effect, an exploratory statistical analysis of variance has been attached as supplementary data to assess the possible effects of TMS on *distractor-to-target* spatial compatibility effects (DTP; Appendix K). The following results from this exploratory ANOVA will be discussed: rTMS over rDLPFC (*MD*= 29.56, *SE*= 7.95, *p*=.005) did have an effect on spatial compatibility effect but there was no interaction with WM load. The simple effect of overall faster RTs for rDLPFC stimulation compared to No TMS condition does not provide compelling evidence for brain stimulation effects but rather is attributable to generic increase in somatosensory effects. There was also a main effect of TMS Site *F*(2.48, 79.44) =5.87, *p*=.002, ηp2 =.16 and significant two-way interactions between WM load and DTP for RTs (*F*(3, 96) =16.10, *p*< .001, ηp2 =.34) and error rates (*F*(1, 32) =45.67, *p*< .001, ηp2 =.59). Overall, TMS effects were not observed for neither the magnitude of distractor "object" compatibility effect nor distractor "spatial" compatibility effect with working memory load.

4.4 Discussion

The significant main effect of WM load for both RTs and error rates confirmed that the WM load manipulation was successful. More specifically, participants were slower and less accurate in response when four items were maintained in WM versus one item. Additionally, when the distractor mismatched the WM item, participants committed more errors and reacted slower overall. In line with Wang and colleagues (2018), the mean RT for the rDLPFC condition was significantly quicker relative to the No TMS condition. There was no significant replication of Load Theory predictions, i.e., increased distractor compatibility effect under high WM load (Lavie et al., 2004) in contrast to findings from Experiments 1 and 2. Under conditions where WM resources were taxed, there was a greater influence of the distractor item even when the duration of display was short (i.e., 200ms). When the task is more difficult, the effect of the WM distractor may be enhanced, leading to both costs and benefits. One interpretation was that distractor items matching the WM item may have been used strategically to find a target more efficiently (Woodman & Luck, 2007; Mazza et al., 2011) whilst salient mismatching (i.e., task-irrelevant) distractors were not successfully suppressed, as longer RTs were recorded in this condition (Theeuwes, 2010).

The complementary analysis (Appendix K) was performed to gain a more comprehensive view of the “object” and “spatial” compatibility effects with WM load. This analysis was more comparable to Wang and colleagues (2018) in that the “valid” condition corresponded with the matching DTP condition whereby the target and distractor overlapped spatially. The main effect of TMS Site suggests that facilitation effects were found, i.e., rDLPFC stimulation led to faster RTs for matching DTP versus mismatching DTP (akin to Wang et al., 2018). The interaction between DTP and WM load presented two distinct patterns of findings. Firstly, under low WM load, there was a significant 20ms advantage and reduced errors for mismatching DTP. This is regarded as a ‘disruption’ effect as there was an overall impairment in the ability for participants to disengage from the shared (i.e., matching) spatial location between target and distractor, leading to significantly more errors and slower responses. It can be inferred that the WM guidance effect has been eliminated by TMS when WM load is low (Zhang et al., 2011). Moreover, under high WM load, there was a larger compatibility effect, for errors rates, in the direction of predicted by WM guidance theories (Yan et al. 2016). Enhancements in performance were regarded as ‘counterintuitive’ because disruptions were expected as a result of the summation of rTMS effects (Wang et al., 2018). However, it is plausible that disruption to processes which were usually disadvantageous for the task at hand can benefit task performance (Tadin et al., 2011). Whilst the current findings suggest that WM load effects are not specific to a TMS stimulation site, it may be inferred that the effects of spatial compatibility can be enhanced or impaired depending on WM load.

In relation to the aforementioned theories of attention, the current study has not been able to establish modulations of visual WM load on distractor processing for neither “object” nor “spatial” compatibility (comparable to Allen et al., 2017; Yao et al., 2020). The explanation offered by Yao and colleagues (2020) regarding a non-significant modulation of distractor processing could be a consequence of well-controlled spatial distribution of the memory array. As suggested by Allen and colleagues (2017) to investigate beyond the domain-general executive-based attentional control, the current manipulation of two specialized executive functions, i.e. WM updating and inhibition of distractor processing, still yielded no clear interaction between the two factors. It should be noted that the vast majority of studies have used dual-task paradigms whilst the current study contributes to single-task scenarios. Although the current experimental design may not have targeted Dilution Theory predictions directly (Tsal & Benoni, 2010), the dilution phenomenon may be applicable, as the stimuli were identical to those used in Experiment 2.

However, the behavioural results do not show strong support for the occurrence of dilution in the absence of electrophysiological data.

A limitation was an absence of effect on TMS stimulation sites, which could be due to the current rTMS experimental manipulations not being effective to modulate the distractor interference effect with WM load. An absence of the rPPC effect could be due to not stimulating at an intensity that can elicit the effect, which is 65% of maximum stimulator output (Ellison et al., 2007; Lane et al. 2012; Kehrer et al., 2015). However, Wang and colleagues (2018) delivered stimulation at a fixed intensity of 45% of the maximum stimulator output, whereas the current study averaged at 63%, which should be adequate. The rPPC effect may be sensitive to the timing of TMS pulse delivery, which has been identified as 100ms after onset of search array (Fuggetta et al., 2008; Kehrer et al., 2015), and short-lasting duration of rTMS after-effects (Sandrini et al., 2011). Another limitation would be the possibility of verbal encoding, and future experiments may circumvent by utilising memory test display colours within the same colour category (Wang et al., 2018). The current study included only the shape task, which may deter participants from verbally encoding items in the high load condition, but this cannot be ruled out completely. Some researchers have tackled the issue of verbal encoding with the inclusion of an articulatory suppression task (e.g. Roper & Vecera, 2014).

In terms of the stereotaxic neuro-navigation used to locate the TMS sites, these systems cannot fully address individual differences in structure-function relationships (Sack et al., 2009). A follow-up study should include structural brain images from individual subjects and fMRI data (i.e. level of activation) to further investigate the target-protection account of DLPFC-based control (Feredoes et al., 2011; Wang et al. 2020). Another limitation was that network-level effects and interactions were not examined, i.e. stimulating more than one brain region. Ruff and colleagues (2009) postulate that TMS can affect not only the stimulated region but also remote neural regions interconnected with the stimulation site. Future TMS-EEG combined protocols may benefit from improving the current rTMS artefact removal pipeline which had originally been created for single-pulse TMS (Rogasch et al., 2017), apply an alternative approach, i.e. theta burst stimulation (Hoy et al. 2016), or deliver TMS outside a particular time window to preserve the EEG signal. It should also be acknowledged that TMS is limited to the depth of superficial cortical regions, and currently available coils offer limited spatial resolution of a few centimetres in diameter (Thielscher & Kammer, 2002).

Another region of interest in TMS studies investigating visual attention is the frontal eye fields (FEFs) which are part of the FPN (Nobre et al., 2003; Ro et al., 2003; Smith et al., 2005; Neggers et al., 2007). Eye movements cannot be induced by TMS in healthy participants but can be used to interfere with the processing of visually and non-visually guided saccades (Vernet et al., 2014). For instance, TMS interferes with discrimination of targets in conjunction search tasks (Muggleton et al., 2003; O'Shea et al., 2004). In particular, the right FEF has been involved in attentional shifts towards both hemi-fields in contrast to the left FEF involved in shifting attention to the contralateral (i.e., right) hemi-field (Mesulam, 1981; Corbetta & Shulman, 2011). Other relevant TMS/ERP studies have demonstrated the effects of TMS applied to the right FEF in the early stages of attentional shifting (Taylor et al., 2006; Torriero et al., 2019).

In conclusion, there was no strong support for Load Theory predictions in the current experiment despite attempts to disrupt the nodes within the dorsal FPN during the onset of a singleton pop-out distractor array (Duecker & Sack, 2015). For instance, it is unclear why the current experiment has not corroborated findings from Experiments 1 and 2. The complementary analysis, which was of secondary interest, has revealed spatial compatibility effects between target and distractor items which were not explicitly designed to benefit or impair task performance. One possibility was that participants engaged more with the visuo-spatial sketchpad than phonological loop (Baddeley, 2000). The current findings cannot be fully explained by a single theory of attention, but previous investigations have alluded to alternative explanations for an absence of WM load effects such as a well-controlled spatial distribution of the visual array (Allen et al., 2017).

Chapter 5: General Discussion

5.1 Overview of Findings

The main aim of this thesis was to investigate the working memory (WM) load predictions from the Load Theory of Selective Attention and Cognitive Control (Load Theory; Lavie et al., 2004) within a single task-setting. One modification that was attempted was to specify the type of "executive control" load, and the specific functions of interest were 'updating' and 'inhibition'. Single-task settings have received less research interest compared to dual-task settings (Bayramova et al., 2020). The current paradigm (modified delayed match-to-sample combined with visual search with the distractor array inserted during the retention interval between initial sample and target) is novel and not the conventional choice of 'updating' task such as a flanker or n-back tasks. On the other hand, researchers studying attentional capture would utilise attentional blink or cuing paradigms. The strength of the delayed match-to-sample task is that different stages of memory such as encoding, maintenance and retrieval can be delineated in time. It is also a modified version of the Sternberg task which can also be used in animal populations when testing for prefrontal cortex functions (Goldman-Rakic, 1987). The adaptability of the novel task is also a strength, as different manipulations were executed, i.e. varying WM load conditions and combining the task with neuroscience techniques.

Previous studies investigating WM load predictions of Load Theory have found results in favour of the theory (De Fockert et al., 2001; Konstantinou et al., 2014) as well as contradictory (Simon et al., 2016; Sreenivasan & Jha, 2007) and null results (Allen et al., 2017; Yao et al., 2020). In the current series of experiments, there was partial support for Load Theory's WM load predictions specific to distractor processing. Firstly, there was increased distractor processing with increased WM load in **Experiment 1 (Chapter 2)** which plateaued at set-size 3. Experiment 1 tackled the limitation of Load Theory operationalisation of low versus high WM load in the form of a memory task for fixed or random digit order. Load Theory may be able to account for null effects in the low WM load condition, i.e. effects are detected when there is a situation where items are competing for attention and a stimulus needs to be prioritised over another. However, researchers would have to consider alternative theories such as specialized load theory (Park et al., 2007), dilution theory (Tsal & Benoni, 2010), the TEDTOFF theory (Sörqvist & Rönnberg, 2014) or visual WM capacity theories (Vogel & Machizawa, 2004; Bays et al., 2011) for a comprehensive explanation for set-size differences.

Secondly, there were conflicting results in **Experiment 2 (Chapter 3)** depending on the behavioural measure of interest. Given that error rates should be moving in a similar direction as RTs, it was surprising to find opposing behavioural results. The inclusion of ERPs has aided in the debate, especially where attentional processes are concerned, although Lavie has not personally engaged with this specific technique. Other researchers, some of whom have applied EEG, found support for Load Theory in terms of perceptual load, but these instances utilised stimuli with manipulation of valence (e.g. emotion portrayed by faces) and reward (Kim et al., 2005; Park et al., 2007; Ward et al., 2019; Watson et al., 2019; 2020). In contrast to faces, using a set of neutral stimuli such as basic shapes avoids the issue of ‘special’ recognition as humans are able to extract emotional valence from a glimpse (approximately 50-100 ms) due to its social importance (Peng et al., 2019). The minority of EEG studies tackling WM load effects were both in favour of (Wei & Zhou, 2020) and against (Berti & Schorger, 2003; Rose et al., 2005; Scharinger et al., 2015; Kim et al., 2017) the expected results. It should be noted that the aforementioned studies were primarily interested in the N1 and P3 components associated with visual perception and stimulus evaluation respectively. The EEG data from Experiment 2, specifically the well-established ERP component associated with attentional allocation (N2pc) has shown that participants were more likely to be distracted by peripheral distractors when WM load was low. This is complementary to researchers interested in visual WM capacity and contralateral delay activity (Ikkai et al., 2010; Luria et al., 2016).

Thirdly, there was much to be addressed where frontal and parietal regions were concerned in relation to WM and selective attention. In particular, Lavie and colleagues (2004) attributed high WM load effects to frontal lobe damage but have not yet provided causal evidence for WM load. In a recent study, task performance in low load conditions was impaired, whereas high load (1 item versus 2 items) benefitted from TMS delivered to the right parietal region (Kiyonaga et al., 2021). From a methodological perspective, it has been recommended by Duecker & Sack (2015a) to use surface electrodes in combination with a sham TMS coil to minimise somatosensory effects being mistaken as brain stimulation effects. Moreover, the causal role of the dorsolateral prefrontal and posterior parietal cortices in WM remains unresolved even when investigations have converged on right-hemispheric effects/dominance (Duecker et al., 2013; Duecker & Sack, 2015b). The primary data analyses from **Experiment 3 (Chapter 4)** concerned with object compatibility effects demonstrated minimal support for Load Theory predictions. In contrast, the secondary analyses where spatial compatibility effects were considered showed that TMS stimulation can impair or enhance task performance as a function of load. This was similar to auditory selective attention (Bayramova et al., 2020) in which TMS induced disruptive effects under low WM load and showed the opposite effect for high WM load. Spatial compatibility effects were not of primary interest for the thesis as a) participants were instructed to ignore the distractor, b) spatial position was randomized and would not facilitate performance and c) the EEG data from Experiment 2 suggests that eye movement strategies were likely not used, which implies that spatial processing did not differ across conditions.

5.2 Limitations and Future Directions

A limitation of the experimental design was that only familiar shapes and colours (e.g. blue square) were used. This alongside a lengthy encoding phase (i.e. 2,000 ms) may have encouraged verbal strategies. Future investigations should incorporate a pure baseline condition for comparison with non-verbalized shapes to minimize the occurrence of verbal encoding (e.g. Lin & Yeh, 2014) or test for memory with varying hues rather than distinctly different colours (Wang et al., 2018). A current gap in the literature would be the inclusion of obscure colours (without a well-known name) rather than common colours. It has been postulated by Blazenkhova and Kozhevnikov (2009) that beyond the original dichotomy of visual processing, which was either verbal or visual, there is evidence for spatial imagery as a cognitive strategy. The tentative assumption is that spatial visualizers might not maintain a lot of pictorial details when processing images in order to develop efficient spatial transformation abilities. Non-verbalized shapes are ideal candidates for visual search because there are no pre-existing associations attached to them (Wagemans et al., 2008). A logical follow-up study could investigate visual complexity (e.g. crowded visual array) and consider cognitive strategy, as the current study offers an evenly-distributed spatial visual search array of homogeneous circles containing a singleton pop-out item. The maximal duration for responses would be 1,200 ms or less to minimize the effect of memory degradation in VSTM capacity (Todd & Marois, 2004) and verbal encoding (Zhang & Luck, 2015).

In Lavie and colleagues' (2004) paper, their analyses targeted the effect of working memory load on distractor compatibility effects for each participant. The "interference" effect was calculated as the difference between mismatching and neutral conditions whilst a "facilitation" effect was calculated as the difference between compatible and neutral conditions. An analogous analysis could not be computed as there was no equivalent neutral condition in the current study. A homogeneous display was included in Experiment 2, but this was not considered to be adequate as there was no “pop-out” element. The TEDTOFF model (Sörqvist & Rönnberg, 2014) outlined clear predictions for cross-modality effects. The susceptibility towards auditory distraction was reduced as the difficulty of visual task increased. The authors emphasised the influence of WMC on focal-task engagement, with high-capacity individuals being less distracted by background noise compared to low-capacity individuals. Thus, future studies may be able to draw conclusions regarding the level of concentration between high and low WMC groups (Sörqvist & Marsh, 2015) and extend across modalities, e.g. auditory distractors (Simon et al., 2016). It has been suggested that self-report measures (regarding task difficulty across task conditions) can circumvent the issue of circularity of reasoning. The inclusion of pupilometric measures such as increased pupil dilation reflects increased effort (Koelewijn et al., 2012; Scharinger et al., 2015). Another suggestion is that a single pulse TMS protocol could be applied for the TMS-EEG combined method (Fuggetta et al., 2006) with the benefit of probing time sensitive effects (i.e. 100ms after stimulus onset for the rPPC) and the application of existing TMS artefact removal software (Rogasch et al., 2017).

Specific to tasks which have been testing WM load, these studies are working to an assumption that they are tapping the same selective attention processes. However, it may be that a Stroop task involves dimensional attention whereas a flanker task depends on the spatial separation of components (Chajut et al., 2009). The acknowledgement of variability in the choice of tasks may benefit researchers who are still actively researching WM load effects and their interaction with distractor processing (e.g. Simon et al., 2016). This discrepancy was somewhat addressed when Konstantinou and colleagues (2014) were able to distinguish between maintenance and cognitive control processes to explain opposing distractor interference effects such as distractor interference increasing with more cognitive control load. Although the review paper by Murphy and colleagues (2016) had listed the criticisms and limitations associated with Load Theory, it may be that the dominant theory’s applications in the real world (e.g. eyewitness testimony) outweigh its flaws. Other studies have further supported the issue of ecological validity, and some psychologists have tried to implement distraction into the background of children's surrounding environments (Rodrigues & Pandeirada, 2018). In a similar vein, a few visual attention researchers have introduced attentional zoom as an alternative explanation (Chen & Chan, 2007; Cave & Chen, 2016) that may be more stable than visual WM load. Their experimental manipulations offer a similarly controlled design for testing the WM side of Load Theory whilst ensuring for minimal influence of perceptual load (verbal rehearsal). Their current stance was that a wider attentional window size does increase distractor processing (Lee & Jeong, 2020). Alternatively, it may be advantageous to probe further into *capacity load* versus *resolution load* (Zhang & Luck, 2015). Zhang and Luck (2015) posited that perceptual load effects could reflect an increased need for resolution rather than loading perception per se.

5.3 Conclusion and Practical Applications

Overall, the conclusions from the thesis acknowledge that Load Theory is a useful theoretical framework for testing the effects of loading the visual system both perceptually and on executive processes. However, certain experimental tasks and data collection measures can contribute to occasions where an excess of WM load does not always lead to increased distractor interference. One recommendation for future investigations as outlined by Lleras and colleagues (2013) is that researchers should acknowledge the distinction between 'distractor interference' and 'distractibility'. The former involves within-task effects whereas the latter encompasses the preoccupation of the mind by stimuli that were not intended to be processed in the first place. Thus, a distractor which is task-relevant will not tell us anything about distractibility. In addition, the field may benefit from labelling WM load effects as the efficiency of visual processing amongst several 'candidates' in a given display. Research specific to Load Theory is limited by the inconsistencies in operationalising the term ‘cognitive’ load which may refer to general executive control processes or WM which is not unitary (Baddeley, 2003). There should be clarity with regards to what effects can be observed when the general executive component (which arguably has been researched more thoroughly) was strained compared to the specific components (i.e. shifting, updating and inhibition). In accordance with EF researchers, it may be worth administering multiple EF tasks tapping into certain functions to gain a more comprehensive view.

In terms of practical applications, the findings from the thesis may transfer to situations more aligned with visual search rather than those requiring situational awareness. It may be fruitful to extrapolate the current findings to scenarios in which high levels of visual detection is required, such as radiography and airport security (Wolfe, 2010). Another promising avenue of investigation which would benefit from the inclusion of context includes foraging studies or multiple object tracking. Most visual search studies have been criticised as lacking ecological validity in that the experimental tasks are not reflective of real-life tasks. Foraging is an interesting context, as the everyday visual environment can be noisy, and it can be adapted for more modern-day applications such as searching for car keys.

Appendix A

Information sheet for Experiment 2. Changes were made between experiments such as the length of the experimental session and the inclusion of details regarding TMS (Experiment 3).

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STUDY INFORMATION SHEET

This study investigates how your brain is able to allocate selective attention in the face of distractions using electroencephalography (EEG). EEG is a safe and non-invasive technique of measuring brain activity which involves the application of application a head cap, which is a piece of elasticised material into which individual adaptors containing the sensors are mounted. A conductive gel (a harmless saline solution) will be used to fill each electrode. This amplifies neuronal activity which is recorded with millisecond precision.

The study will take place in the EEG laboratory of the Department of Psychology (Cognitive Labs: 2nd Floor Rm 2021 Parkstead House). You do not have to take part in this study if you do not want to. If you decide to take part, you may withdraw at any time without having to give a reason and without penalties. Before you decide whether you want to take part, it is important for you to read the following information carefully and discuss it with others if you wish.

Upon arrival at the laboratory, the experimenter will ask you to fill out a consent form before the procedure begins. The EEG set-up will then take place. The measurement of brain signals with EEG system will involve the wearing of a head cap rather like a swimming cap with sensors connected to it. Each sensor will record tiny electrical brain signals via a conductive gel, which feels rather like ordinary hair gel. Prior to applying the gel, we will need to clean the areas of skin around your eyes and ears where some of the sensors will be placed, using alcohol. The conductive gel will then be applied using a syringe that will make light contact with your scalp. If you find this at all uncomfortable, please inform us and we will stop the procedure. Please note that you are likely to get small residues of the gel in your hair after the session. The gel is non-toxic, non-odorous and washes off easily with water. So, some of the gel will wipe off but you will need to wash off the remainder either here (there are private facilities for you to do this) or at home. You may have a few red marks on your face from the head cap or electrodes, but these should disappear after a few minutes. The electronic equipment has been subjected to full electrical testing by the manufacturers and is used only to *measure* tiny pulses of electrical activity from your brain and not to apply electricity to you. Please be assured that the whole process, and the use of head-cap electrodes for measuring EEG, is safe.

You will be seated and asked to perform a memory task with the head cap on. This task lasts approximately 1 hour, including breaks. Secondly, there is a task measuring alerting, orienting, and executive control which lasts for 10 minutes. You will be asked to respond with a key press the direction in which the cue appears. The third task is a working memory capacity task (duration: 10 minutes). You will be required to remember the spatial position of shapes and make judgements regarding the symmetry of visual displays. Altogether, the experiment is going to take 2 hours 30 minutes. You will be given regular rest breaks. Your personal information will be kept confidential, and only authorized people will have access to it for research purposes only.

Unless otherwise stated, we are generally looking for healthy people aged between 18 and 40 years. The experiments take place in relatively small, darkened rooms. You should not volunteer if you have a skin condition on your scalp. You should also not have a history of, or be taking medication for, psychiatric disorders or diseases (e.g., ADHD, depression, anxiety, or mood disorders), or neurological disorders or diseases (e.g. stroke, head injury, epilepsy, seizures, brain tumours, brain surgery, Parkinson's Disease). It is important to be fit, well rested and avoid consuming alcohol 24 hours prior to taking part in an EEG experiment as this will affect the data. Also, it helps if you do not use any hair-care products like conditioner, oils or wax or hair accessories (bobbles, clips, ties) in your hair. Ideally, hair must be in a natural hairstyle with no extensions, dreadlocks, cornrows, weaves or perms. Finally, if you are wearing contact lenses but also have a pair of spectacles you could wear, it is advisable to bring your spectacles, because some participants complain of dry eyes when they are doing our experiments.

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Appendix B

Consent forms for Experiment 2. Minor changes were made between experiments such as the length of the sessions, expected number of participants to be recruited and the inclusion of details regarding TMS (Experiment 3).

University of Roehampton London

Participant Identification Number (ID Number):

|___|___|___| (to be filled in by the researcher)

PARTICIPANT CONSENT FORM

Title of research project: The role of cognitive load in distraction suppression.

Brief description of research project and what participation involves:

We are requesting your participation in a study (lasting around 2 hours, 30 mins in total) that aims to further our understanding of how we direct visual attention towards task-relevant goals in the face of distractions: the task is to determine whether the target (i.e. shape or colour) is the same or different from the initial cue whilst ignoring a distractor. We are hoping to recruit around 48 participants for the study, which will take place within the Cognitive Lab, Department of Psychology, University of Roehampton.

You will be asked to perform three tasks. First, you will be asked to remember a visual display that will appear on the screen. Following this, you will be asked to respond with a key press as to whether the target shape/colour matches the initial display. You will have to respond as quickly and accurately as possible. This task lasts approximately 1 hour, including breaks. Secondly, there is a task measuring alerting, orienting, and executive control which lasts for 10 minutes. You will be asked to respond with a key press the direction in which the cue appears. The third task is a working memory capacity task (duration: 10 minutes). You will be required to remember the spatial position of shapes and make judgements regarding the symmetry of visual displays.

While you perform the tasks, we will record tiny electrical signals from your scalp (see EEG information sheet), which will involve wearing a head cap rather like a swimming cap. The cap has sensors connected to it for recording tiny electrical brain signals via a conductive gel, which feels rather like ordinary hair gel. Prior to applying the gel, we will need to clean the areas of skin around your eyes and ears where some of the sensors will be placed, using alcohol. The conductive gel will then be applied using a syringe that will make light contact with your scalp. If you find this at all uncomfortable, please inform us and we will stop the procedure. Some of the gel will wipe off but you will need to wash off the remainder either here (we have private facilities for you to do this) or at home. You may have a few red marks on your face from the head cap or electrodes but these should disappear after a few minutes. The electronic equipment has been subjected to full electrical testing by the manufacturers, and is used only to *measure* tiny pulses of electrical activity from your brain and not to apply electricity to you. Please be assured that the whole process, and the use of head-cap electrodes for measuring EEG, is safe. (Please see full details of the EEG procedure within the EEG information sheet.) The preparation of the head cap and recording of EEG data may take up to one hour.

Please do not take part if:
a) you are under 18 years of age; b) you have a skin condition on your scalp; c) you have any history of, or are taking medication for, psychiatric disorders or diseases (e.g., ADHD, depression, anxiety, or mood disorders), or neurological disorders or diseases (e.g. stroke, head injury, epilepsy, seizures, brain tumours, brain surgery, Parkinson's Disease).

Right to withdraw:
You are under no obligation to finish the experiment and can withdraw participation from the whole experiment or any part of it at any point without needing to justify your decision. You can also request for your data to be withdrawn at any time after participation in the study. In order to do this, please contact the investigator with your participant number, which you will find on the Debrief Form. Please be aware, however, that data may already have been anonymised or published in aggregate form at the time of request. Finally, if you are a student who is volunteering for course credits as part of an undergraduate module, please be advised that there will be no adverse consequences in relation to assessment for your degree if you decide to withdraw.

Confidentiality and anonymity:
All data relating to your participation in this study will be held securely in password protected computer files and locked filing cabinets. While the lead investigator has collaborators at other

institutions that will be involved with the proposed studies (i.e. Dr Philip Duke, University of Leicester), none of the research will be conducted at these other institutions and collaborators will not have access to raw data or names of participants. No one outside of the research team will have access to your individual data, and anonymity of processed data will be protected at all times. Researchers involved in the study will be unaware of any links between your identity and the data collected. Signed consent forms will be kept separately from all other data. Your identity will not be passed on to anyone who is not involved in this study, and will be protected in the publication of any findings. Personal data will be kept for 10 years and anonymised data will be retained indefinitely.

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Consent statement:

I agree to take part in this research, and am aware that I am free to withdraw at any point without giving a reason by contacting Rebecca Saw. I understand that if I do withdraw, my data may not be erased but will only be used in an anonymised form as part of an aggregated dataset. I understand that the personal data collected from me during the course of the project will be used for the purposes outlined above in the public interest.

By signing this form, you are confirming that you have read, understood and agree with the University's Data Privacy Notice for Research Participants and the University's Data Protection Policy.

The information you have provided will be treated in confidence by the researcher and your identity will be protected in the publication of any findings. The purpose of the research may change over time, and your data may be re-used for research projects by the University in the future. If this is the case, you will normally be provided with additional information about the new project.

I have read and understood the Information Sheet provided. I have been given a full explanation by the investigator(s) of the nature, purpose, location and likely duration of the study and of what I will be expected to do. I have been given the opportunity to ask questions on all aspects of the study and have understood the advice and information given as a result.

I am 18 years or over, do not have a skin condition on my scalp, and have no history of, and am taking no medication for, any psychiatric disorders or diseases, or any neurological disorders or diseases.

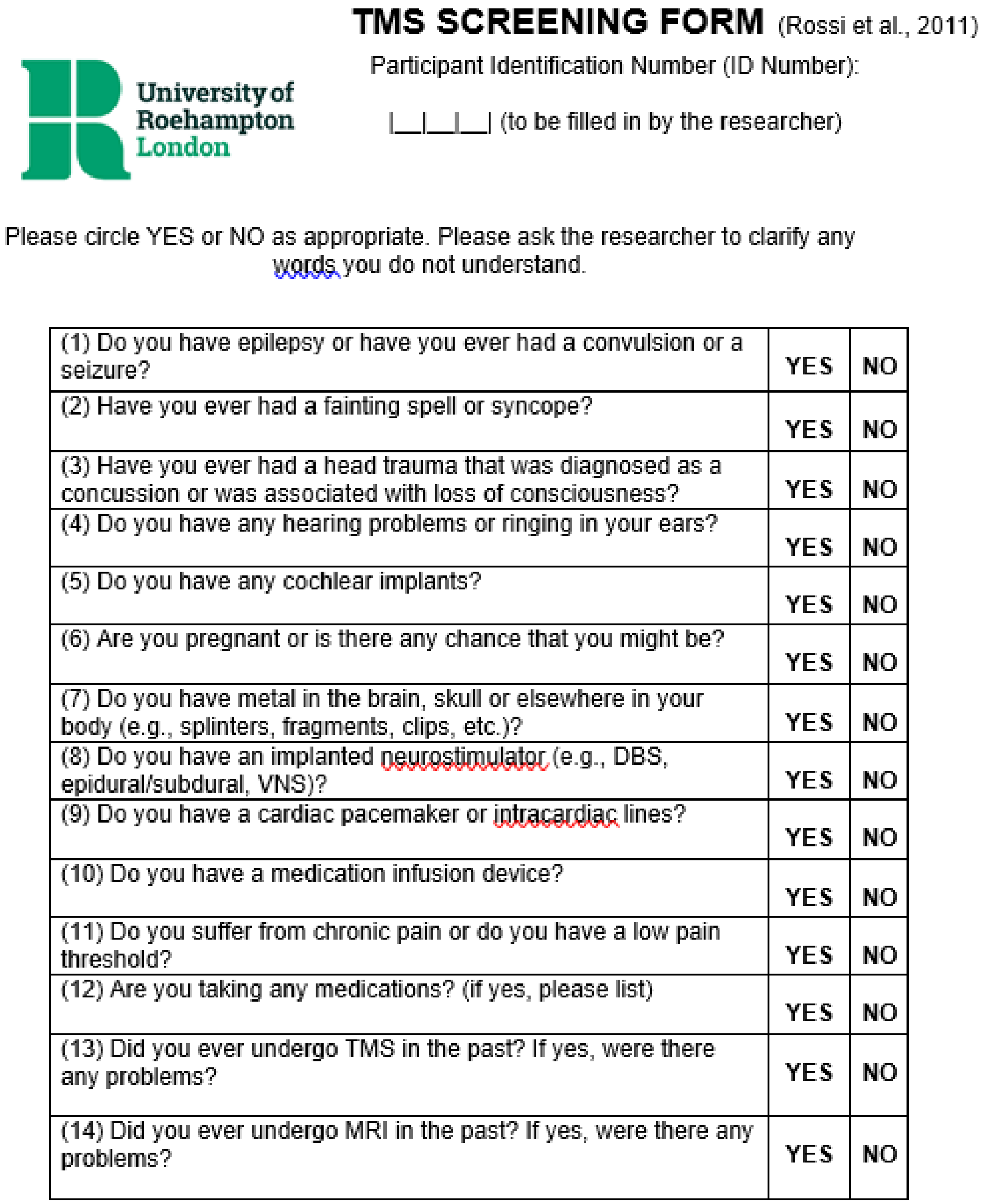
Name ………………………………….

Signature ………………………………

Date ……………………………………

Please note: if you have a concern about any aspect of your participation or any other queries please raise this with the investigator. However, if you would like to contact an independent party please contact the Head of Department.

Head of Department contact details:
Dr Diane Bray
Department of Psychology
University of Roehampton
Whitelands College
Holybourne Avenue
London SW15 4JD
d.bray@roehampton.ac.uk
020 8392 3617



University of
Roehampton
London

TMS SCREENING FORM (Rossi et al., 2011)

Participant Identification Number (ID Number):

|__|__|__| (to be filled in by the researcher)

Please circle YES or NO as appropriate. Please ask the researcher to clarify any words you do not understand.

(1) Do you have epilepsy or have you ever had a convulsion or a seizure?	YES	NO
(2) Have you ever had a fainting spell or syncope?	YES	NO
(3) Have you ever had a head trauma that was diagnosed as a concussion or was associated with loss of consciousness?	YES	NO
(4) Do you have any hearing problems or ringing in your ears?	YES	NO
(5) Do you have any cochlear implants?	YES	NO
(6) Are you pregnant or is there any chance that you might be?	YES	NO
(7) Do you have metal in the brain, skull or elsewhere in your body (e.g., splinters, fragments, clips, etc.)?	YES	NO
(8) Do you have an implanted neurostimulator (e.g., DBS, epidural/subdural, VNS)?	YES	NO
(9) Do you have a cardiac pacemaker or intracardiac lines?	YES	NO
(10) Do you have a medication infusion device?	YES	NO
(11) Do you suffer from chronic pain or do you have a low pain threshold?	YES	NO
(12) Are you taking any medications? (if yes, please list)	YES	NO
(13) Did you ever undergo TMS in the past? If yes, were there any problems?	YES	NO
(14) Did you ever undergo MRI in the past? If yes, were there any problems?	YES	NO

Appendix C

Screening form for Experiment 3, adapted from Rossi et al. (2009).

Appendix D

Instructions for Experiments 2 and 3. Response key mappings were reversed for even numbered participants.

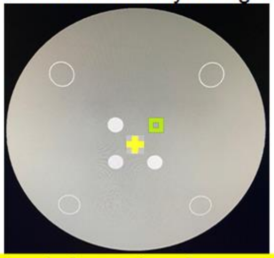
INSTRUCTIONS FOR ODD PARTICIPANT – Visual Working Memory and distraction suppresssion

On each trial, you will see four stimuli in a sequence: 1) Task Cue & Informative Cue, 2) Distractor, and 3) Target on screen.

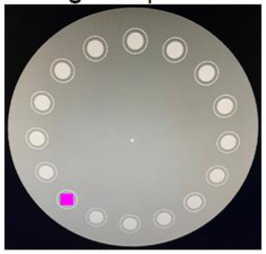
If the task CUE is a **Yellow +** then you will have to perform a **SHAPE comparison task**.

Press the **LEFT** mouse button with your left index if the **Target** shape is **DIFFERENT** from the **Informative cue** shape(s).

Press the **RIGHT** mouse button with your right index if the **Target** shape is the **SAME** as the informative cue shape(s).



Informative Cue



Distractor

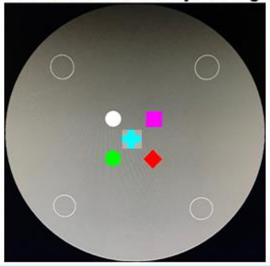
Target

In the example, the target shape "☐" is **SAME** as the cue shape "☐". They are both boxes☐. **[Press Right]**

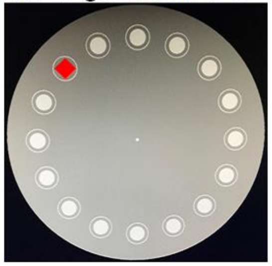
If the task CUE is a Bright Blue + then you will have to perform a COLOUR comparison task.

Press the **LEFT** mouse button with your left index if the **Target** colour is **DIFFERENT** from the **Informative cue** colour(s).

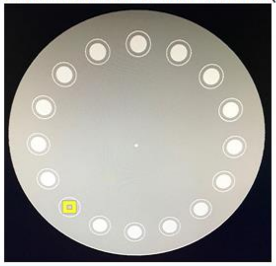
Press the **RIGHT** mouse button with your right index if the **Target** colour is the **SAME** as the informative cue colour(s).



Informative Cue



Distractor



Target

In the example, the target colour "yellow" is **DIFFERENT** from the cue colours "magenta", "green" and "red" **[Press Left]**

Appendix E

Participant Identification Number (ID Number):

|___|___|___| (to be filled in by the researcher)

PARTICIPANT DEBRIEF

Title of Research Project: The role of working memory load in distraction suppression_EXP2

Researchers: Rebecca Saw (lead) and Dr Giorgio Fuggetta from the Department of Psychology at Roehampton University.

Thank you very much for taking part in this part of our study. We greatly appreciate your contribution.

Summary of details of participation: You completed two computer tasks assessing attention and visual working memory capacity respectively and a visual paradigm whilst an electroencephalography (EEG) system and transcranial magnetic stimulation (TMS) system was monitoring your brain activity.

The study was designed assess individual differences in cognitive functions such as attention and working memory capacity in the normal population of undergraduate students.

All data gathered during this study will be held securely and anonymously. If you wish to withdraw your data from the study, please contact us with your participant number (above) and your information will be deleted from our files. Please be aware, however, that data may already have been published in aggregate form at the time of request, but your identity will always be protected in the publication of any findings.

Should you have any concern about any aspect of your participation in this study, please raise it with the investigator. However, if you would like to contact an independent party please contact the Head of Department.

Lead investigator: Rebecca Saw (PhD student) E-mail: sawr@roehampton.ac.uk	
Co-investigator: Dr Giorgio Fuggetta, Department of Psychology, University of Roehampton,	**Head of Department:** Dr Diane Bray, Department of Psychology, University of Roehampton, Whitelands

Whitelands College, Holybourne Avenue, London SW15 4JD E-mail: giorgio.fuggetta@roehampton.ac.uk Telephone: 020 8392 3409	College, Holybourne Avenue, London SW15 4JD E-mail: d.bray@roehampton.ac.uk Telephone: 020 8392 3627

If you are a student at Roehampton University and are troubled or worried about any aspect of the study, or issues it may have raised, you may find it helpful to contact one of the following who will be able to advise you on agencies that can deal with your particular concern:

Wellbeing Team:

Student Welfare Officers:

Froebel Sophie Carney	Sophie.Carney@roehampton.ac.uk	Tel.: 020 8392 3304
Digby Stuart Nicola Hallam	Nicola.Hallam@roehampton.ac.uk	Tel.: 020 8392 3200
Southlands Jo Eskdale	J.Eskdale@roehampton.ac.uk	Tel.: 020 8392 3402
Whitelands Emily Cookson	Emily.Cookson@roehampton.ac.uk	Tel.: 020 8392 3502

The Sleep Council:	www.sleepcouncil.org.uk	Tel.: 080 0018 7923
Samaritans:	www.samaritans.org/	Tel.: 116 123

If you feel your concerns are more serious or complex you may wish to contact the **Student Medical Centre** at HealthandWellbeing@roehampton.ac.uk Tel.: 020 8392 3679**.** If you are not a student at Roehampton University**,** please contact your GP.

Appendix F

Tables depicting RGB values used in Experiments 1-3, respectively.

	Red	Green	Blue
Blue	0	101	169
Brown	134	79	0
Cyan	0	107	107
Dark Grey	21	21	21
Green	0	110	0
Grey	54	54	54
Magenta	162	0	162
Purple	117	26	248
Red	179	0	0
White	95	95	95
Yellow	96	96	0
Bright Cyan	0	172	172
Bright Yellow	155	155	0

(i)

	Red	Green	Blue
Blue	0	0	255
Brown	96	65	0
Cyan	0	83	83
Dark Grey	18	18	18
Green	0	85	0
Grey	38	38	38
Magenta	130	0	130
Purple	104	0	200

	Red	**Green**	**Blue**
Red	146	0	0
White	72	72	72
Yellow	74	74	0
Bright Red	170	0	0
Bright Green	0	101	0

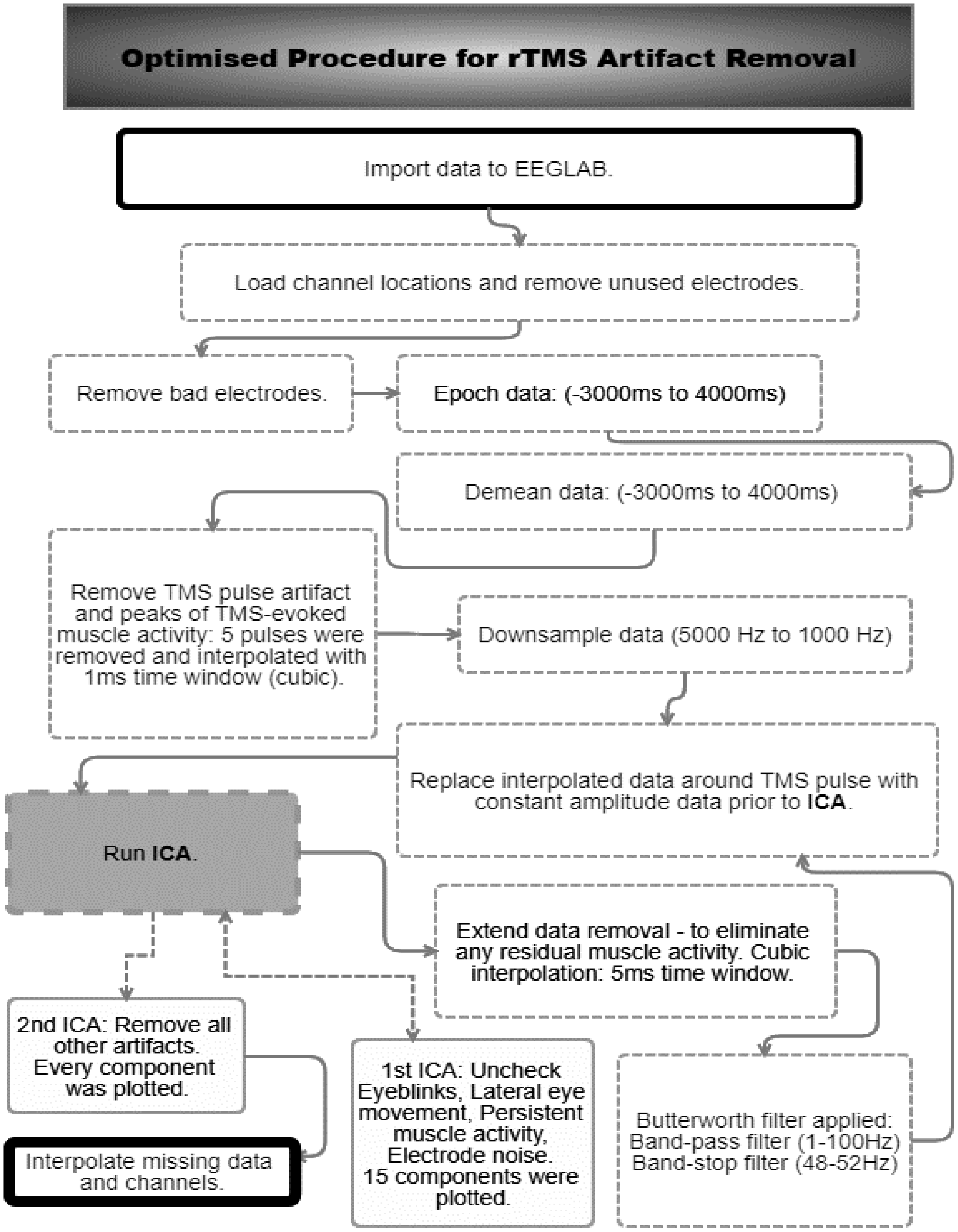
(ii)

	Red	**Green**	**Blue**
Blue	0	0	255
Brown	107	71	35
Cyan	0	91	91
Dark Grey	44	44	44
Green	0	92	0
Grey	24	24	24
Magenta	135	0	135
Purple	105	0	210
Red	151	0	0
White	79	79	79
Yellow	83	83	0
Bright Green	0	111	0
Bright Red	175	0	0

(iii)

Appendix G

Pipeline of artifact removal adapted from Rogasch et al. (2017) and can be found here for Experiment 3.



Appendix H

Experiment 1 Complementary Analysis: Cowan's K (Capacity Estimates)

The number of objects encoded was estimated using Cowan's K formula for each set size. K= (hit rate + correct rejection rate - 1)*N, where K is the number of objects encoded and N is the number of objects presented (found in Cowan, 2001; Todd & Marois 2004). A repeated-measures ANOVA was implemented to estimate the number of objects encoded for each set size (1, 2, 3, 4 items) and Distractor Type (Matching, Mismatching). The K values represent the number of correctly remembered items. It is important to note that Cowan's K is the difference in capacity between conditions within participants rather than an absolute estimate of capacity in terms of number of discrete items.

ANOVA of Cowan's K values revealed a significant main effect of WM load $F(1.28, 29.52) = 58.81$, $p<.001$, $\eta_p^2 = .72$ showing that participants remembered the most amount of items with set-size 4 (M=2.15, SE=.20), set-size 3 (M=1.85, SE=.15), set-size 2 (M=1.45, SE=.10) and then set-size 1 (M=0.81, SE=.04) condition. Pairwise comparisons revealed that each set-size significantly differed from each other (*ps*<.001). The biggest difference was between set-size 1 versus 4 whereas the smallest difference between set-size 3 and 4. There was a significant main effect of Distractor Type $F(1,23) = 41.22$, $p<.001$, $\eta_p^2 = .64$ revealing that participants were remembering less items accurately for mismatching distractors (M=1.42, SE=0.12), than matching distractors (M=1.70, SE=0.13**)**. The two-way interaction between WM Load x Distractor Type $F(1.74, 40.11) = 7.87$, $p=.002$, $\eta_p^2 = .26$ was significant. Post-hoc comparisons revealed that Cowan's K values were significantly different between distractor types across all WM load conditions (*p*s =.005) except for set-size 1 (*p*= .09). The biggest difference was within set-size 3 whereas the smallest difference was within set-size 2.

Appendix I

CFQ (This questionnaire will take approximately 5 minutes)

DIRECTIONS: The following questions are about minor mistakes which everyone makes from time to time, but some of which happen more often than others. We want to know how often these things have happened to you in the ***last six months***. Please circle the appropriate number.

Please circle the number that applies	Very Often	Quite Often	Occasionally	Very rarely	Never
1. Do you read something and find you haven't been thinking about it and must read it again?	1	2	3	4	5
2. Do you find you forget why you went from one part of the house to the other?	1	2	3	4	5
3. Do you fail to notice signposts on the road?	1	2	3	4	5
4. Do you find you confuse right and left when giving directions?	1	2	3	4	5
5. Do you bump into people?	1	2	3	4	5
6. Do you find you forget whether you've turned off a light or a fire or locked the door?	1	2	3	4	5
7. Do you fail to listen to people's names when you are meeting them?	1	2	3	4	5
8. Do you say something and realise afterwards that it might be taken as Insulting?	1	2	3	4	5
9. Do you fail to hear people speaking to you when you are doing something else?	1	2	3	4	5
10. Do you lose you temper and regret it?	1	2	3	4	5
11. Do you leave important letters unanswered for days?	1	2	3	4	5
12. Do you find you forget which way to turn on a road you know Well but rarely use?	1	2	3	4	5
13. Do you fail to see what you want in the supermarket (although it's there?)	1	2	3	4	5

14. Do you find yourself suddenly wondering whether you've used word correctly? 1 2 3 4 5

15. Do you have trouble making your mind up? 1 2 3 4 5

16. Do you find you forget appointments? 1 2 3 4 5

17. Do you forget where you put something like a newspaper or a book? 1 2 3 4 5

18. Do you find you accidently throw away the thing you want and keep what you meant to throw away – as in the example of throwing away the matchbox and putting the used match in your pocket? 1 2 3 4 5

19. Do you daydream when you ought to be listening to something? 1 2 3 4 5

20. Do you find you forget people's names? 1 2 3 4 5

21. Do you start doing one thing at home and get distracted into doing something else (unintentionally)? 1 2 3 4 5

22. Do you find you can't quit remember something even though it's 'on the tip of your tongue'? 1 2 3 4 5

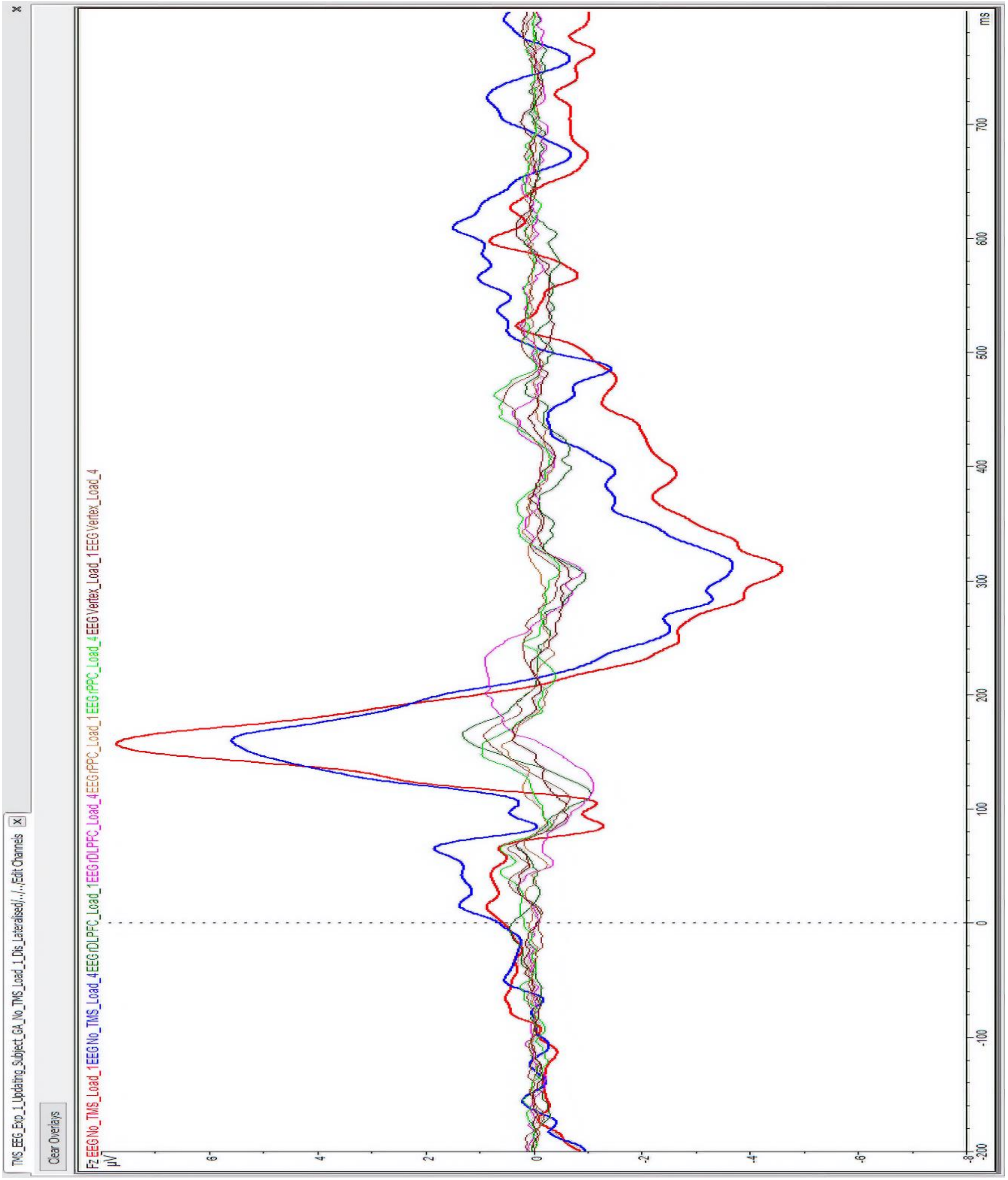
23. Do you forget what you came to the shops to buy? 1 2 3 4 5

24. Do you drop things? 1 2 3 4 5

25. Do you find you can't think of anything else to say? 1 2 3 4 5

Appendix J

TMS Artefact Removal: the signal of TMS conditions were harshly removed compared to the No TMS condition.



Appendix K

Experiment 3 Exploratory Analyses: Distractor-to-Target Spatial Compatibility Effects

Only correct responses and RTs longer than 150 ms were analysed with 2.23% of trials removed from analysis. RTs (milliseconds) and percentage error rates of correct responses were analyzed with a 3-way repeated measures ANOVA. The within-subjects factors were WM load set-size (1 versus 4 items), Distractor-to-Target Position (DTP; different hemifield, same hemifield) and TMS site (rDLPFC, rPPC, Vertex and No TMS).

Table 4.3
ANOVA Results for Mean RTs in the DMTS Task.

Source	*Df*	*F*	Sig.	Partial Eta Squared
Site	**2.48, 79.44**	**5.87**	**.002**	**.16**
WML	**1, 32**	**147.51**	**<.001**	**.82**
DTP	1, 32	2.71	.11	.08
Site * WML	3, 96	1.35	.26	.04
Site * DTP	**3, 96**	**4.23**	**.01**	**.12**
WML * DTP	**1, 32**	**16.10**	**<.001**	**.34**
Site * WML * DTP	3, 96	.17	.92	.01

Note: Site= Site of TMS, WML= Working Memory Load, DTP= Distractor to Target Position and df= degrees of freedom. Significant main effects and interactions are bolded.

Reaction Times

ANOVA of RTs revealed a significant main effect of WM Load *F*(1, 32) =147.51, *p*<.001, ηp2 =.82 showing that participants were slower to respond to the high WM load condition (*M*=758.97, *SE*=27.08) than the low WM load condition (*M*=618.54, *SE*=22.88). A main effect of TMS Site *F*(2.48, 79.44) =5.87, *p*=.002, ηp2 =.16 revealed that participants were slowest in response to no TMS stimulation (*M*=709.56, *SE*=23.83), Vertex stimulation (*M*=683.60, *SE*=25.35), rPPC stimulation (*M*=686.93, *SE*=25.65), and quickest to respond with rDLPFC stimulation (*M*=674.94, *SE*=24.94). Pairwise comparisons revealed a significant difference between the no TMS stimulation and rDLPFC stimulation conditions (*MD*= 34.61, *SE*= 10.12, *p*=.01) whereas other pairwise comparisons were not significant (*p*> .05). The two-way interaction TMS Site x Distractor-to-Target Position *F*(3, 96) =4.23, *p*= .01, ηp2 =.12 was significant. Post-hoc comparisons showed that RTs were significantly different (*p*= .002) between same DTP (*M*=687.17, *SE*=25.96) versus different DTP (*M*=662.72, *SE*= 24.46) with rDLPFC stimulation. The two-way interaction WM load x Distractor-to-Target Position *F*(3, 96) =16.10, *p*< .001, ηp2 =.34 was significant. Post-hoc comparisons revealed that RTs were significantly different (*p*< .001) only between matching DTP (*M*=628.89, *SE*=23.61) versus mismatching DTP (*M*=608.20, *SE*=22.42), under low WM load. All other comparisons were not significant (*ps*> .05).

Figure 4.4

The rTMS Stimulation Site x Distractor-to-Target Position Interaction for Mean RTs.

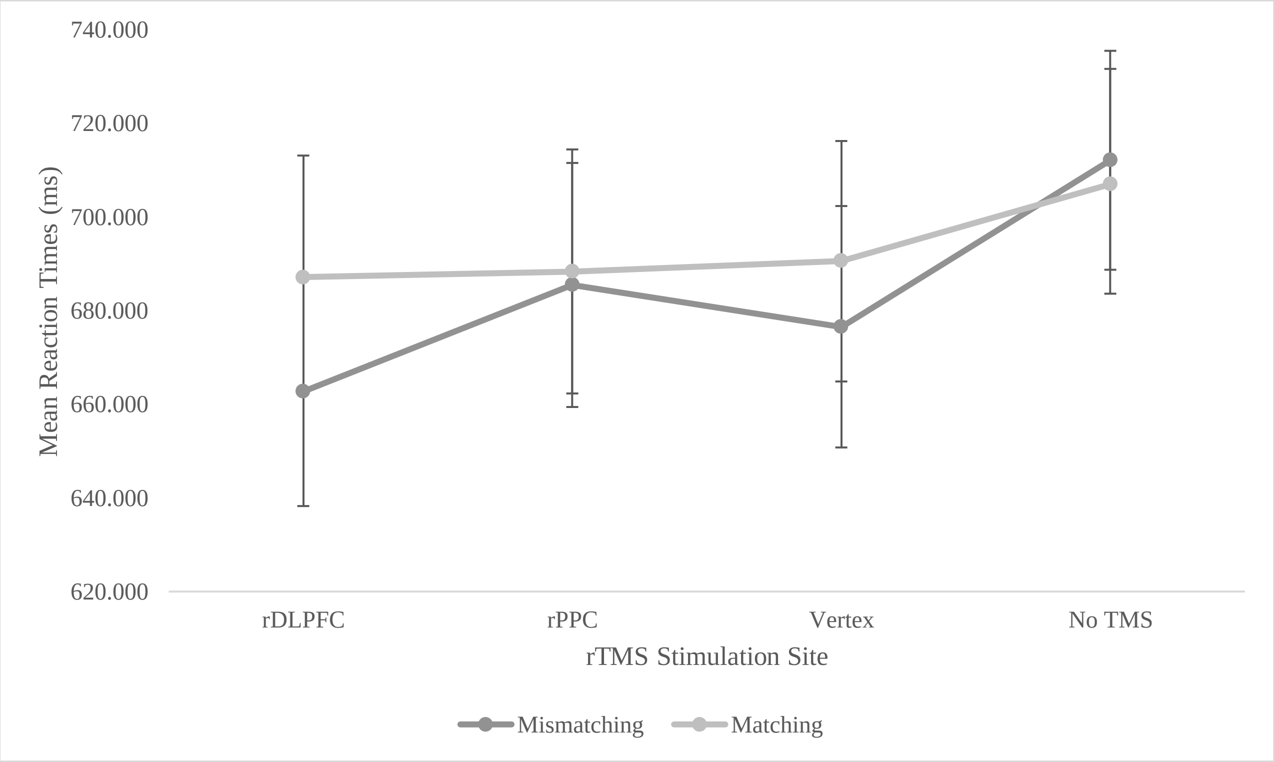


Table 4.4
ANOVA Results for Mean Error Rates in the DMTS Task.

Source	*Df*	*F*	Sig.	Partial Eta Squared
Site	3, 96	2.34	.08	.07
WML	**1, 32**	**229.07**	**<.001**	**.88**
DTP	**1, 32**	**8.04**	**.01**	**.20**
Site * WML	3, 96	1.86	.14	.06
Site * DTP	3, 96	.37	.77	.01
WML * DTP	**1, 32**	**45.67**	**<.001**	**.59**
Site * WML * DTP	3, 96	.53	.67	.02

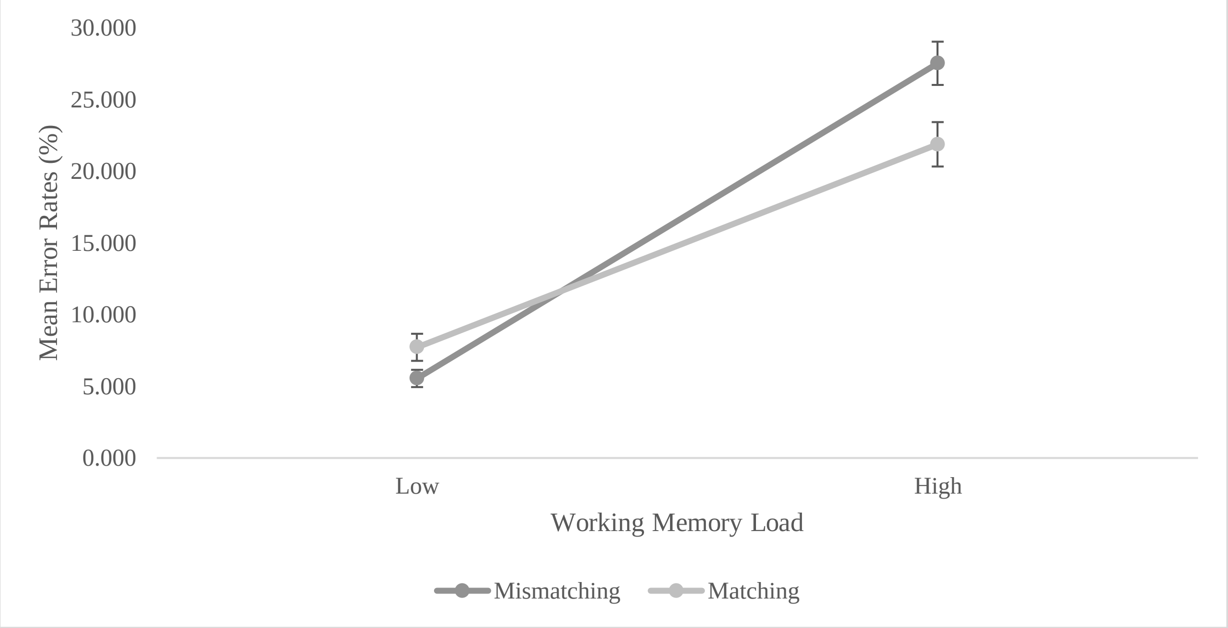
Note: Site= Site of TMS, WML= Working Memory Load, DTP= Distractor to Target Position and df= degrees of freedom. Significant main effects and interactions are bolded.

Error Rates

ANOVA of error rates revealed a significant main effect of WM load *F*(1, 32) =229.07, *p*<.001, ηp2 =.88 showing that participants were least accurate in responding with high WM load (*M*=24.73, *SE*= 1.45) versus low WM load (*M*=6.64, *SE*=.72). A main effect of Distractor-to-Target Position *F*(1, 32) =8.04, *p*= .01 ηp2 =.20 revealed that participants were less accurate at responding to distractors which mismatched (*M*=16.56, *SE*= .94) than distractors which matched (*M*=14.81, *SE*=1.01) the subsequent target. The two-way interaction WM Load x Distractor Type *F*(1, 32) =45.67, *p*< .001, ηp2 =.59 was significant. Under low WM load, means differed significantly (*p*=.003) between mismatching DTP (*M*= 5.55, *SE*=.60) and matching DTP (*M*= 7.73, *SE*=.94) with more errors committed in the latter condition. Under high WM load, means differed significantly (*p*<.001) between mismatching DTP (*M*=27.55, *SE*=1.51) and matching DTP (*M*=21.90, *SE*=1.55). This interaction demonstrated that there was a larger congruency effect in the high WM load condition. All other comparisons were significant (*ps*> .05).

Figure 4.5

Mean Error Rates of WM Load by Distractor-to-Target Position Interaction.



Distractor Spatial Compatibility Effect

The magnitude of spatial compatibility effect of RTs and error rates of the difference between conditions: Distractor-to-Target Position Different minus Distractor-to-Target Position Same. A 2-way repeated measures ANOVA with the within-subjects factors; TMS site (rDLPFC, rPPC, Vertex, No TMS) and WM load (low, high) was conducted.

ANOVA of RTs revealed a significant main effect of TMS Site *F*(3, 96) =4.23, *p*=.007, ηp2 =.12 and WM load *F*(1, 32) =16.10, *p*<.001, ηp2 =.34. The 2-way interaction of TMS Site x WM load *F*(3, 96) =.17, *p*=.92 was not significant. ANOVA of error rates revealed no significant main effect of TMS Site *F*(3, 96) =.38, *p*=.77. There was a significant main effect of WM load *F*(1, 32) =45.67, *p*<.001, ηp2 =.59 showing that the DTP spatial compatibility effect was less under low load (M=-2.17, SE=.66) than high load (M=5.65, SE=.99). The 2-way interaction of TMS Site x WM load *F*(3, 96) =.53, *p*=.67 was not significant.

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