Exploring the Relationship between Working Memory Capacity and Task Switching

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Abstract

Tests of task switching and working memory capacity are both thought to assess executive attentional control. Given that they are purported to measure the same underlying cognitive construct, one would expect a relationship between performance on these tasks. However, preliminary research has largely failed to find such an association. This thesis explored the association between task switching and working memory capacity to determine why previous research has failed to find this expected relationship. Experiment 1 examined this relationship across three commonly used task switching paradigms which differed in the amount of environmental support available to participants as they completed the task. Experiment 2 explored the role of task difficulty on the switching paradigm because working memory capacity and cognitive control are most related under particularly taxing conditions. Both of these Experiments failed to find a clear relationship between task switching and working memory capacity. These findings replicated much of the previous research in this area and suggested that task difficulty and paradigm choice could not explain the failure of previous research to find a relationship between these two constructs. Experiment 3 explored the role of cue switch costs. The task switching paradigm confounds cue switching and task switching, and it has been argued that switch costs may largely be explained by the cost of the cue switching. If this is the case, and cue switch costs do not index attentional control, then it is not surprising that previous research has failed to find a relationship between task switching and working memory capacity. Experiment 3 found evidence of cue switch costs, but ‘true’ task switch costs remained. After the confounding effect of cue switching was controlled for, the expected negative linear relationship between working memory capacity and task switching was found. Participants with higher working memory capacity had smaller switch costs, indicative of better performance. The results of this thesis point to the importance of making careful experimental design decisions when using the task switching paradigm. This is particularly important when the goal of such research is to index attentional control, especially in the context of individual differences research.

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List of Abbreviations

ACC	Accuracy
ACT-R	Adaptive Control of Thought-Rational
AR	Alternating Runs
CoV	Coefficient of Variation
CSI	Cue-to-stimulus Interval
CSR	Cue-stimulus-response
DLPFC	Dorsolateral Prefrontal Cortex
EF	Executive Function
ERP	Event-related Potentials
fMRI	Functional Magnetic Resonance Imaging
IQR	Interquartile Range
LTM	Long-term Memory
OSF	Open Science Framework
OSpan	Operation Span Task
PFC	Prefrontal Cortex
RCI	Response-to-cue Interval
RotSpan	Rotation Span Task
RSI	Response-to-stimulus Interval
RT	Reaction Time
SymSpan	Symmetry Span Task
VTS	Voluntary Task Switching
WMC	Working Memory Capacity

Chapter 1 – General Introduction

1.1 Executive Functions

The study of executive functioning has flourished in recent years (Diamond, 2013). This is not surprising given the important nature of this construct in our understanding of human cognition. We use our executive functions anytime we do something effortful, requiring concentration and attention. You may find yourself working on a project in your office when you hear a knock at the door. You can instantly shift the focus of your attention to the person at the door, address their query, and then return to your project. Such an event occurs seemingly effortlessly, while unbeknownst to you, a number of executive functions are being utilized. Attention switching is required to shift the focus of your attention from your project to the currently prioritized task of dealing with the query at the door. The change in environmental demands require you to inhibit your desire to continue working and instead adopt a new task goal of effectively addressing the visitor's query. While dealing with the visitor, you must also keep the task goals of your project in working memory so that you can easily return to the task once your interaction with the visitor is complete. We deal with distractions and disruptions like this constantly, and we do so with ease thanks to our cognitive control system. Despite the pervasive use of executive functions in our everyday lives, our understanding of such processes is far from complete.

Although executive functioning has been widely studied, it remains both difficult to measure and define, leading to a lack of agreement and some controversy over what executive functions actually are (Jurado & Rosselli, 2007). Additionally, different terminology is used across different research literatures with the term executive function being largely synonymous with cognitive control (Cohen, 2017). Executive functions can be broadly defined as top-down control processes that effectively regulate our thoughts and behaviours, especially when concentration and attention are necessary (Diamond, 2013; Miyake & Friedman, 2012). Three core executive functions have been proposed; inhibition (overriding a dominant response), working memory (holding and manipulating information in mind), and set-shifting or cognitive flexibility (flexibly switching attention between tasks) (Diamond, 2013; Diamond & Ling, 2016; Miyake et al., 2000). A key feature of these core executive functions is that they show both unity and diversity. It has been proposed that while each of these constructs represents a unique aspect of cognition, they all tap into a common underlying executive ability (Friedman & Miyake, 2017; Miyake & Friedman, 2012; Miyake et al., 2000).

Given such a proposal, one would expect a relationship between tasks designed to measure these core executive function constructs. However, for working memory and task switching, previous research has failed to find support for such a relationship (Hambrick & Altmann, 2015; Kane, Poole, Tuholski, & Engle, 2003; Kane, Conway, Hambrick, & Engle, 2007; Klauer, Schmitz, Teige-Mocigemba, & Voss, 2010; Oberauer, Süß, Wilhelm, & Wittman, 2003). Such findings are perplexing and warrant further research. The goal of the present thesis is to explore the relationship between task switching and working memory in more detail. An examination of the degree to which these executive functions are related has an important bearing on our understanding of these cognitive processes.

This chapter will provide an introduction to task switching and working memory. This will include a discussion of the types of tasks used to measure these constructs and will explore theoretical accounts of performance on these tasks. Research that has begun to examine the relationship between task switching and working memory will be discussed, highlighting the important need for further research in this area. Finally, an overview of the thesis will be provided.

1.2 Task Switching

Task switching involves flexibly shifting ones attention as the demands of a task change (Monsell, 2003). This ability is fundamental to effectively navigating through our lives as multitasking is an essential skill. Although it seems like we can switch our attention between tasks with ease, there is actually a cost involved. Responses are slower and more error prone when we switch between tasks compared to when we repeat them. This cognitive cost, referred to as switch cost, has generated a great deal of interest and has been widely studied (Kiesel et al., 2010; Koch, Poljac, Muller, & Kiesel, 2018; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010). A number of task switching paradigms have been developed to examine these switch costs in more depth (Grange & Houghton, 2014).

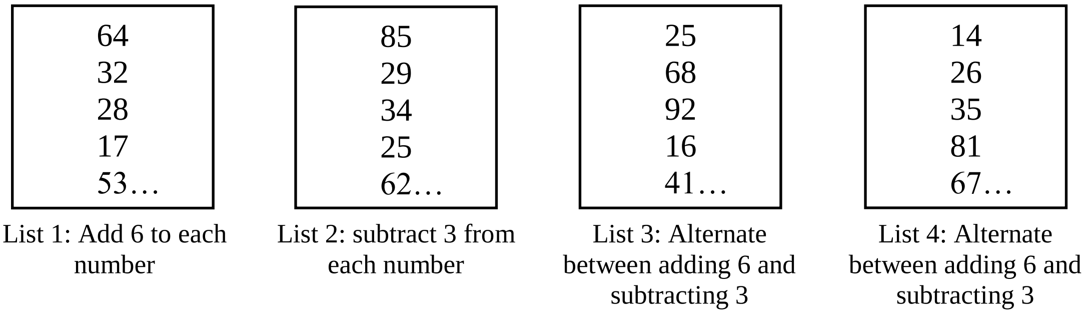
1.2.1 Measuring task switching.

Task switching was first studied in the laboratory by Jersild (1927), using the list paradigm. On this task, participants are provided with four lists of numbers and timed while they perform a particular task on each list. On the first list, they must add six to each number. On the second list, they subtract three from each number. Finally, on the third and fourth lists they alternate between adding and subtracting. Participants are slower to perform the alternating lists than the repeating lists, thus displaying switch costs (Jersild, 1927). A major issue with the list paradigm is that it confounds switch costs with working memory load differences (Vandierendonck et al., 2010). To perform lists one and two, participants only had to keep one task set in mind, either add or subtract. However, on list three, participants had to keep these two task sets in memory at the same time. This increased memory load may account for the differences in reaction time that were found. These findings from the list paradigm were later replicated (Spector & Biederman, 1976), but it wasn't until the 1990's that studies of task switching performance began to flourish.

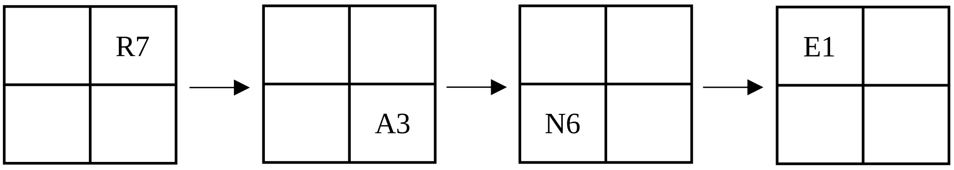
To address the limitations of the list paradigm, the alternating runs (AR) paradigm was developed (Rogers & Monsell, 1995). During this task, participants are presented with a number-letter pair on each trial, and they must classify the number as odd or even or the letter as a consonant or vowel. Participants are required to switch between performing these tasks on every other trial in a predictable manner, e.g., letter task, letter task, number task, number task. To reduce the memory load, the stimuli are presented in a 2x2 grid and they rotate clockwise on each trial. If the number-letter pair appears in the top half of the grid, participants perform the number task, and if it appears in the bottom half of the grid, they perform the letter task. Reaction time on switch trials can then be compared to repeat trials to assess switch costs (Rogers & Monsell, 1995). In this procedure, switch and repeat trials occur in the same block, thus equating memory load and addressing flaws inherent in the list paradigm. One issue with the alternating runs paradigm is that it does not allow for fine experimental control over timing. For example, it does not allow us to determine the exact timing of when participants begin preparing for the upcoming task (Grange & Houghton, 2014).

The explicit cuing procedure was designed to allow for more experimental control of the timing of cognitive operations (Meiran, 1996). Like the alternating runs paradigm, this procedure has participants perform one of two tasks on bivalent stimuli. Unlike the alternating runs paradigm, the tasks are ordered randomly, and each trial is preceded by a cue indicating which task is to be performed on the upcoming stimulus. Participants do not know if they will be switching tasks or repeating the same task until the cue is presented. This paradigm allows the experimenter to manipulate the amount of preparation time participants have by lengthening the cue-to-stimulus interval (CSI). The time between the response to the stimulus and the start of the next cue (response-to-cue interval, RCI) can also be manipulated to vary the time available for the decay of the previous task set (Meiran, 2014). See Figure 1 for an overview of some of the most commonly used task switching paradigms.

A) List Paradigm

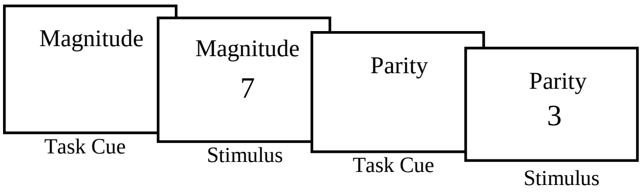


B) Alternating Runs Paradigm



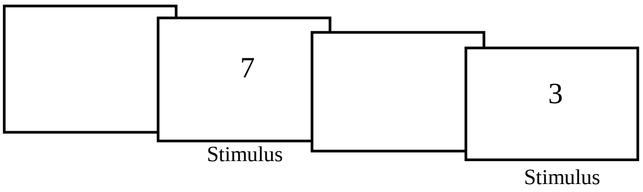
Task: If the stimulus is in the upper quadrant, indicate if the number is odd or even. If it is in the bottom quadrant, indicate whether the letter is a consonant or vowel.

C) Explicit Cuing Paradigm



Task: Magnitude task: Indicate whether the stimulus is < or > 5. Parity task: indicate whether the number is odd or even.

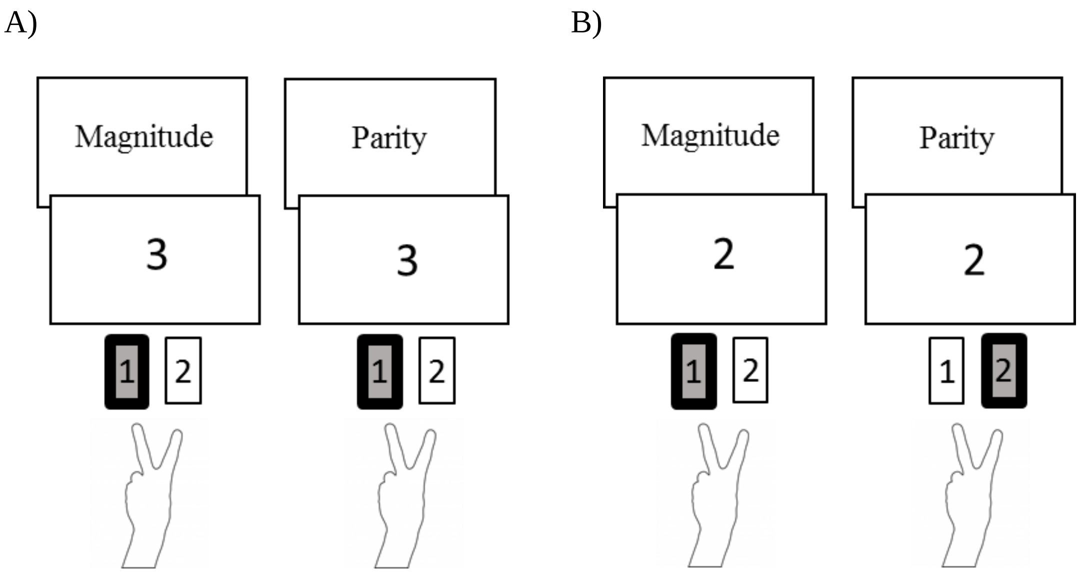
D) Voluntary Task Switching Paradigm



Task: Use left hand to do magnitude task. Use right hand to do parity task. You may choose which task to perform on each trial.

Figure 1. Commonly used paradigms for measuring task switching. A) On the list paradigm, participants work through 4 columns of numbers performing different operations in each column. Switch costs are calculated by looking at the total time difference to complete lists 1 and 2 versus 3 and 4. B) The alternating runs paradigm is predictable. The stimulus moves around the grid in a clockwise manner so participants always know what the upcoming task will be. C) On the explicit cuing paradigm, a cue is presented instructing the participant of the task to be performed. The tasks are presented in a random sequence so that participants are unable to predict the upcoming task. D) On the voluntary task switching paradigm, participants choose which task to perform on each trial. Participants must perform the two tasks equally and in a random order. For B, C, and D, the calculation of switch costs is the same. Switch costs = the difference in reaction time between switch trials and repeat trials.

In both the alternating runs and explicit cuing paradigms, responses are made using the same response keys for both tasks. For example, on the magnitude-parity task, participants are asked to respond to the magnitude of a number on some trials, by pressing 1 if the number is less than five and 2 if the number is greater than five. On other trials they are asked to complete the parity task by pressing 1 if the number is odd and 2 if it is even. Congruent trials are those in which the correct response key is the same for both tasks (e.g., 3), and incongruent trials require different responses depending on the task (e.g., 2), as shown in Figure 2. In addition to measuring switch costs, task switching paradigms allow for the examination of response congruency effects. This is the consistent finding of faster response times to congruent stimuli as compared to incongruent stimuli (Meiran & Kessler, 2008; Vandierendonck et al., 2010). This phenomenon is frequently reported in the task switching literature, however compared to switch costs, congruency effects have been studied much less frequently (Meiran & Kessler, 2008).



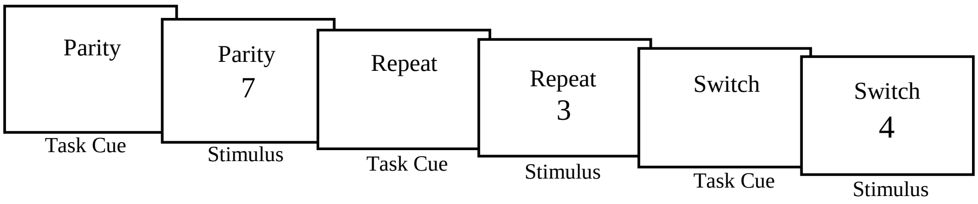
Task Rules:
Parity Task – press 1 if the number is odd, press 2 if the number is even.
Magnitude Task – press 1 if the number is <5, press 2 if the number is >5.

Figure 2. Congruency in the task switching paradigm. Each trial begins with a cue, followed by the target stimulus and participants must respond by pressing the number 1 or 2 based on the task rules. A) For a congruent stimulus, the response is the same, regardless of the task cue. The correct answer is 1 for both the magnitude and parity tasks. B) For an incongruent stimulus, the response differs depending on which task has been cued. Shading highlights the correct answer.

In recent years, the explicit cuing procedure, which is the most widely used task switching paradigm (Jost, De Baene, Koch, & Brass, 2013; Meiran, 2014), has been criticised for not measuring task set shifting (Jost et al., 2013). It has been argued that rather than having to switch task sets on switch trials, participants can successfully complete the task by doing the same thing on every trial. Participants see a cue and a stimulus and form them into a compound which can be used as a joint retrieval cue to retrieve the correct response from long-term memory (LTM) (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Schneider & Logan, 2005). This theory will be explored further in the next section, but it is particularly important for the measurement of task switching because it suggests that task cues play an important role in the generation of switch costs.

This compound-cue retrieval account led to the creation of several new switching paradigms which move away from cuing the specific task on each trial. For instance, the transition-cuing paradigm provides cues indicating whether to repeat the previous task or to switch to the other task. It does not provide a specific task cue, thus eliminating the ability to form cue-target compounds (Forstmann, Brass, & Koch, 2007). The task-span procedure also attempts to prevent compound-cue retrieval by requiring participants to memorize a series of task cues before the actual task stimuli are presented, and then performing the tasks in the order of the memorized cues once the stimuli appear (Logan, 2004). It has also been argued that in the explicit task switching paradigm, each time a cue switches, the task switches, confounding these two processes. To investigate this, double cuing paradigms have been used which involve 2:1 cue to task mappings so that cue switch costs can be dissociated from task switch costs (Logan & Bundesen, 2004; Mayr & Kliegl, 2003). These paradigms have not been researched as widely as the alternating runs and explicit cuing procedures, but they do raise some interesting questions about the effectiveness of traditional task switching paradigms (Grange & Houghton, 2014). See Figure 3 for an overview of these paradigms.

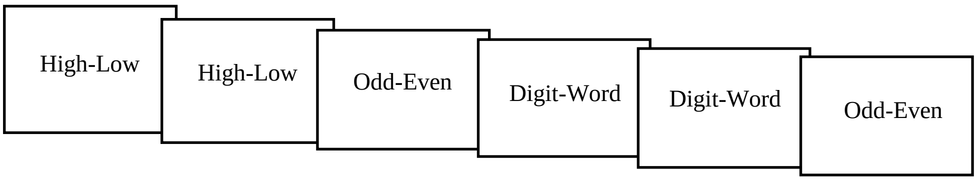
A) Transition Cuing Paradigm



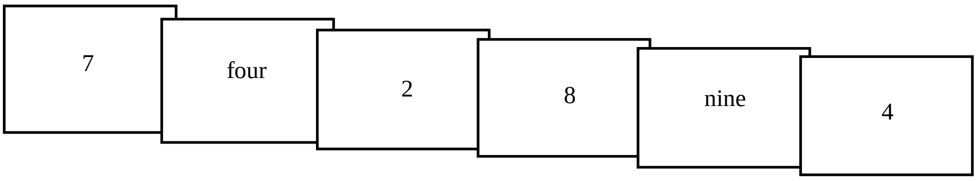
Tasks: Parity task: indicate whether the number is odd or even. Magnitude task: Indicate whether the stimulus is < or > 5.
Cues: “Repeat” and “Switch”.

B) Task Span Procedure

Study Phase:

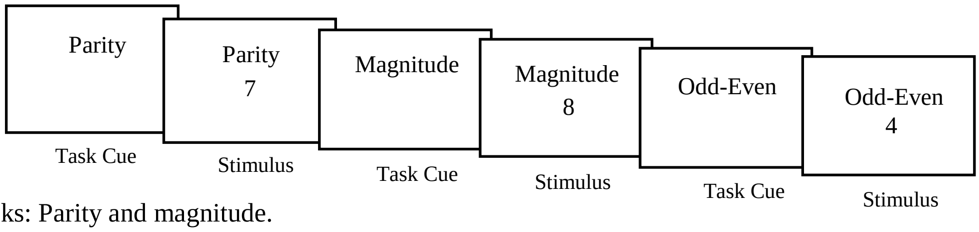


Test Phase:



Tasks: Parity, magnitude, and form. Form task: indicate whether the number is a digit or a word.
Cues: “Odd-Even”, “High-Low”, “Digit-Word”. Cues presented in separate block.

C) 2:1 Cue-to-task mapping Paradigm



Tasks: Parity and magnitude.
Cues: Parity task: cued by “Parity” and “Odd-Even”. Magnitude task: cued by “Magnitude” and “High-Low”

Figure 3. Task switching paradigms designed to minimize the effects of task cuing. A) On the transition cuing paradigm, each block begins with a semantic cue. The remainder of the block does not use specific cues. Instead, participants are instructed to either repeat the same task that was completed on the previous trial, or switch to the other task. Eliminating specific cues blocks the ability to form cue-stimulus compounds. B) On the task span procedure, participants first complete a study phase in which they memorize the order of the cues. In a later test phase, they implement the tasks instructed by the cues on a series of stimuli. This approach eliminates the ability to form cue-stimulus compounds. C) On the 2:1 cue-to-task mapping paradigm, two cues are used for each task. This allows for greater consideration of the role of task cues.

Another task switching paradigm which is increasing in popularity is the voluntary task switching procedure (VTS; See Figure 1) (Arrington & Logan, 2004, 2005; Arrington, Reiman, & Weaver, 2014). In this task, participants must choose which of two tasks to perform on a random basis. Participants perform the tasks with different hands, allowing the researcher to distinguish which task was chosen on each trial. Trials in which the participant switched tasks can be compared with trials in which they repeated the task to examine switch costs. In addition to switch costs, this paradigm allows for the examination of task choice. Analyses can be conducted to examine how frequently each task is selected, and how often participants choose to switch versus repeat. Participants are instructed to perform the tasks randomly and equally often, so measures of task choice provide an index of how well participants are able to do this.

There are clearly a multitude of task-switching procedures. They all involve performing simple tasks on bivalent stimuli, with the relevant task to be performed varying from trial to trial. They all measure switch costs by examining performance on switch trials versus repeat trials, however they differ in a number of important ways. On some paradigms, the task to be performed on the next trial is predictable (list paradigm, alternating runs paradigm) and for others it is random (explicit cuing procedure, voluntary task switching). Some paradigms involve explicit cuing of the upcoming task (explicit cuing paradigm), some involve implicit cuing (alternating runs paradigm), and others have no cues at all (voluntary task switching). It should be noted that although switch costs are universally found in all of these paradigms (Kiesel et al., 2010; Vandierendonck et al., 2010), they are not necessarily comparable (Vandierendonck et al., 2010), with differences in the magnitude of switch costs (Altmann, 2007). Given this fairly large variation in the operational definition of task switching, it is important, when comparing the relationship between task switching and working memory, to closely examine the type of switching paradigm used and to consider using a variety of paradigms. Such an examination will be important in determining whether the relationship between these variables, or lack thereof, is paradigm specific, or a more universal feature.

1.2.2 Theoretical accounts of task switching.

1.2.2.1 Prominent task switching theories.

Several theoretical accounts aim to explain switch costs. The task-set reconfiguration view emphasizes the importance of endogenous executive control in explaining switch costs (Rogers & Monsell, 1995). On each trial in a task switching procedure, participants must adopt a task set, defined as all of the elements required to complete a particular task. When that task set must be switched and a new task set adopted, task-set reconfiguration must take place. This is a time consuming executive process, and switch costs reflect the time needed for this reconfiguration to take place (Monsell, 2003, 2017; Rogers & Monsell, 1995). In contrast, the task-set inertia model emphasizes the role of proactive interference from previous task sets in explaining switch costs. Interference from instructions and stimulus-response mappings that were used on previous trials and remain active lead to slower responses when the task switches (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 2000). Switch costs thus reflect the time required for the system to resolve this interference. Rather than emphasizing endogenous control in the form of reconfiguring task sets, the task-set inertia model suggests that the most important contributor to switch costs is negative priming.

Recent research acknowledges that switch costs result from a number of factors rather than just a single mechanism (Meiran, Chorev, & Sapir, 2000; Monsell, 2003, 2017), and a new theory has bridged previous proposals (Meiran, 1996; Meiran et al., 2000). This theory suggests that switch costs have at least three components, the first is interference from the previous task set as suggested by Allport et al. (1994). This is evident as smaller switch costs are present when more time is provided for the passive dissipation of the previous task set. The second component is task-set reconfiguration, as suggested by Rogers and Monsell (1995). Such reconfiguration is evident because switch costs are reduced when the time between the cue and stimulus presentation is large, allowing for endogenous preparation of the upcoming task (Meiran, 1996). We can use control processes to prepare for the upcoming task by completing task-set reconfiguration before the stimulus appears. However, a third, residual component exists perhaps reflecting some kind of natural limitation. Residual switch costs remain even when plenty of time is given to prepare for the upcoming task. This suggests that we may have some limit regarding how much reconfiguration can take place before the stimulus is actually presented (Meiran et al., 2000).

Although it is generally agreed that task switching requires some kind of top-down executive endogenous control, there is one particular theory that has argued against this. The compound-cue retrieval model suggests that task switching as assessed by the explicit cuing procedure does not require any endogenous control, suggesting that switch costs are not a useful measure of executive functioning (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010). According to this model, in the task switching paradigm, participants process the cue, and then process the target, and then use the cue and target as a joint retrieval cue to find the correct response in memory. The task set is consistent on each trial; use the cue and target to search memory and respond with what you retrieve from the memory search (Logan & Schneider, 2010). There is no need to reconfigure or update the cognitive system on a trial to trial basis. Rather than an act of reconfiguration, switch costs merely reflect the benefit of repeating the same cue rather than any cost of switching. The task switching paradigm confounds cue switches with task switches, so it is argued that the switch cost observed with this paradigm is merely the cost of switching the task cue (Logan & Bundesen, 2004; see Chapter 4 for a more detailed discussion of this idea). This is quite a controversial stance as it calls into question the use of the task switching paradigm as an index of executive function. Others have also suggested that task-set reconfiguration may not be necessary in the task switching paradigm (Altmann, 2003).

These propositions led to a number of studies using the 2:1 cue to task mapping paradigm. With two cues for every one task, cue switch costs and task switch costs can be calculated independently. Although cue switch costs are consistently found using this paradigm, true task switch costs still account for a large portion of the slowed response time on switch trials (Mayr, 2010; Mayr & Kliegl, 2003; Monsell & Mizon, 2006). It is also useful to note that true task switch costs are dissociable from cue switch costs even at the neural level (Brass & von Cramon, 2004; Jost, Mayr, & Rosler, 2008). Awareness of this confound is important, and teasing apart task switch and cue switch costs using the 2:1 cue to task mapping paradigm may be beneficial for isolating the component of task switching which involves endogenous attentional control. This is likely to isolate the component that we would expect to be related to performance on other executive functioning tasks. A recent review cautions against overestimating the importance of such cue-encoding issues when using the task switching paradigm and suggests that use of the standard version of the explicitly cued task switching paradigm is still an effective measure of task switching abilities (Jost et al., 2013). Despite the assertions of the compound-cue retrieval hypothesis, switching paradigms do still seem to measure endogenous control and thus executive functioning. Task-set switching has even be referred to as a “gold-standard measure of executive control” (Kane, Conway, et al., 2007, p. 35).

1.2.2.2 Models of task switching that stress the importance of working memory.

Three other task switching theories, the cognitive control model (Altmann, 2002; Altmann & Gray, 2008), the ACT-R (adaptive control of thought-rational) model (Sohn & Anderson, 2001), and the LTM retrieval model (Mayr & Kliegl, 2000, 2003) have emphasized the important role of memory processes in task switching. Like Meiran et al. (2000), the cognitive control model (Altmann & Gray, 2008) also emphasizes that multiple sources contribute to switch costs, including a strategic control process and an automatic process of decay of the previous task set. However, rather than the strategic control process reflecting task-set reconfiguration as suggested by previous models (Meiran et al., 2000; Rogers & Monsell, 1995), the cognitive control model suggests that it is a reflection of activating relevant codes in episodic memory (Altmann & Gray, 2008). Successful performance in the switching task depends on ones’ ability to maintain access to a task set, which is stored in episodic memory and represents the most recently cued task. Multiple task sets compete for activation and the task set with the highest level of activation will be used to guide behaviour. Cognitive control becomes important in ensuring that the currently cued task code is the one that is more active. Proactive interference from old task codes must be overcome for this to happen (Altmann & Gray, 2008). So, the strategic process of activating the correct task code in episodic memory and the automatic process of decay of the previous task set are important in determining switch costs. This theory heavily focusses on the role of memory processes, and although it uses the term episodic memory, the processes that it refers to could be considered working memory processes.

The ACT-R theory is a general model of cognition which has been applied to both task switching (Sohn & Anderson, 2001) and working memory (Anderson, Reder, & Lebiere, 1996; Lovett, Daily, & Reder, 2000). Like previous theories (Altmann & Gray, 2008; Meiran et al., 2000), the ACT-R model argues for the involvement of both a passive priming process and a cognitive control component to switch costs. ACT-R assumes that LTM has two systems; declarative and procedural knowledge. In task switching, the declarative section holds information regarding cue to task mapping and stimulus-response mapping in chunks. Chunks are chosen from memory based on their level of activity with more recently retrieved chunks having higher activation levels. Because of this, it is easier to call on a chunk that was recently activated, so repeat trials are primed and this contribute to the switch cost. The second component to switch costs involves cognitive control and is responsible for preparation for the upcoming task. Retrieval of the necessary declarative chunk can occur in advance if cognitive control factors are used to resolve the conflict among task productions, which define condition-action rules in procedural knowledge (Sohn & Anderson, 2001). Task goals are used to resolve this conflict before the stimulus arrives, thus speeding up the retrieval of the declarative chunks from working memory. This is more difficult on switch trials, so switch costs reflect inadequate preparation on switch trials as well as the priming benefits of repeat trials. In this model, working memory is the activated portion of declarative memory (Anderson et al., 1996), so the contents of working memory, and the priming and preparation that influence those contents play a fundamental role in task switching performance.

Another model of task switching has also stressed the important role of working memory (Mayr & Kliegl, 2000, 2003). This model suggests that working memory represents only one task set at a time. Each time a task switch occurs, LTM retrieval is required to place the relevant task set in working memory. Switch costs are thought to reflect the time needed to re-retrieve the task set from LTM into working memory, which is a controlled process (Mayr & Kliegl, 2000, 2003). This process must occur on switch trials but not on repeat trials. All three of these memory based switching models (Altmann & Gray, 2008; Mayr & Kliegl, 2000, 2003; Sohn & Anderson, 2001) suggest a potentially important role of working memory in task switching performance. Although they all suggest slightly different mechanisms, they agree that the information needed for successful task performance is stored in working memory, and executive processes are used to ensure the correct information is activated in working memory on each trial.

Most of the recent models of task switching suggest the importance of both a cognitive control component as well as a more automatic priming or decay of previous task set component (Altmann & Gray, 2008; Meiran, 1996; Meiran et al., 2000; Monsell, Sumner, & Waters, 2003; Sohn & Anderson, 2001). The only model to really suggest a complete lack of any cognitive control is the compound-cue retrieval model (Logan & Bundesen, 2003, 2004). However, as noted, recent research has concluded that an endogenous act of control still plays an important role in task switching, and switch costs cannot be entirely accounted for by this model (Monsell & Mizon, 2006). Several of these theories also suggest an important role for working memory in the task switching process (Altmann & Gray, 2008; Mayr & Kliegl, 2000, 2003; Sohn & Anderson, 2001). This potentially important relationship between working memory and task switching will be explored more thoroughly later on. First, we will explore working memory as a construct and as a tool for measuring cognitive functioning.

1.3 Working Memory

Working memory can be defined as a system that allows for the temporary storage of information and the manipulation of that information in order to perform complex cognitive tasks ranging from reasoning to language comprehension (Baddeley, 1992). Although working memory is sometimes used interchangeably with the term short term memory, what makes working memory unique is its ability to manipulate the information that is stored (Baddeley, 2012). The most influential theory of working memory, the multiple component model, was proposed over 40 years ago and still continues to inspire an active area of research today (Baddeley, 2012; Baddeley & Hitch, 1974). This model initially proposed a three component system comprised of a central attentional control system, referred to as the central executive, and two slave systems; the visuospatial sketchpad and the phonological loop, responsible for the storage of visuospatial and sound information, respectively. These two temporary storage systems are both limited in capacity and most studies of the multiple component model have focussed on these storage areas (Baddeley, 2012; Baddeley & Hitch, 1974).

The central executive component is likely to be the most important component of working memory, and yet it is also the least understood (Baddeley, 2003). It was initially conceived of as a homunculus responsible for all of the functions of working memory that needed to be performed outside of the two storage systems. This component is thought to have four potential functions including the ability to focus attention, divide attention, switch between tasks, and communicate with LTM (Baddeley, 1996). More recently, the episodic buffer was introduced to the model

(Baddeley, 2000). This new component is proposed to hold integrated chunks of bound information from different modalities. It is also the link between working memory and perception, and between working memory and LTM. These initial ideas about the structure of working memory including both storage and processing components guided the creation of tasks to measure working memory capacity (WMC).

1.3.1 Measuring working memory capacity.

Baddeley & Hitch's (1974) model clearly emphasizes the importance of both the processing requirements of a task which would be carried out by the central executive and the storage requirements of a task which would involve the visuo-spatial sketchpad and the phonological loop. To investigate the trade-off between these two important components, complex span tasks were created. These tasks were designed to tax the limited resources of both processing and storage (Daneman & Carpenter, 1980). The first complex span task to be developed was the reading span task (Daneman & Carpenter, 1980). On this task, participants are required to read a series of sentences out loud and then report the final word of each sentence. The number of sentences in a series generally ranges in length from two to six. A reading span score reflects the maximum number of sentences that can be read while still perfectly recalling each of the final words. To ensure each sentence is actually read and processed, participants must indicate whether the sentences are true or false (Daneman & Carpenter, 1980), or whether they make sense or not (Unsworth, Redick, Heitz, Broadway, & Engle, 2009).

In the years following the initial development of the reading span task, several other complex span tasks were created, including the counting span task (Case, Kurland, & Goldberg, 1982) and the operation span task (OSpan) (Turner & Engle, 1989). The counting span task involves counting the number of dots on a presented card, and once all of the cards have been presented, the participant must report the number of dots on each of the cards in the correct order (Case et al., 1982). Like the reading span task, the number of cards in each set gradually increases and the number of correct responses is used to calculate the span score. In the operation span task, participants are required to verify answers to arithmetic operations while remembering words that follow each calculation. At the end of a string of operations, they are required to recall each of the words in the correct order, with the number of operations in each set gradually increasing from three to five (Turner & Engle, 1989). More recent versions of the operation span task have become automated, with timing adapted to each individual's mathematical abilities based on the time required to complete the operations during the practice phase (Unsworth, Heitz, Schrock, & Engle, 2005). In this newer version of the task, it is letters that are recalled rather than words so that vocabulary has no influence on performance and the set sizes range from three to seven in order to assess a larger range. A participant's operation span is defined as the sum of all perfectly recalled sets (See Figure 4).

Although the reading span, counting span, and operation span tasks are the three most widely studied complex span tasks (Conway et al., 2005), there are also others that are utilized, including complex span tasks of spatial WMC including rotation span and symmetry span (Foster et al., 2015; Kane et al., 2004). Unlike the task switching tasks described earlier, each of these complex span measures of WMC share a similar structure. They all involve a storage and processing component with items that need to be remembered interspersed with a cognitive task which is not related to the memory task. The only thing that differs across the tasks is the type of processing activity and the type of information that must be recalled. See Figure 4 for a visual depiction of the operation span task.

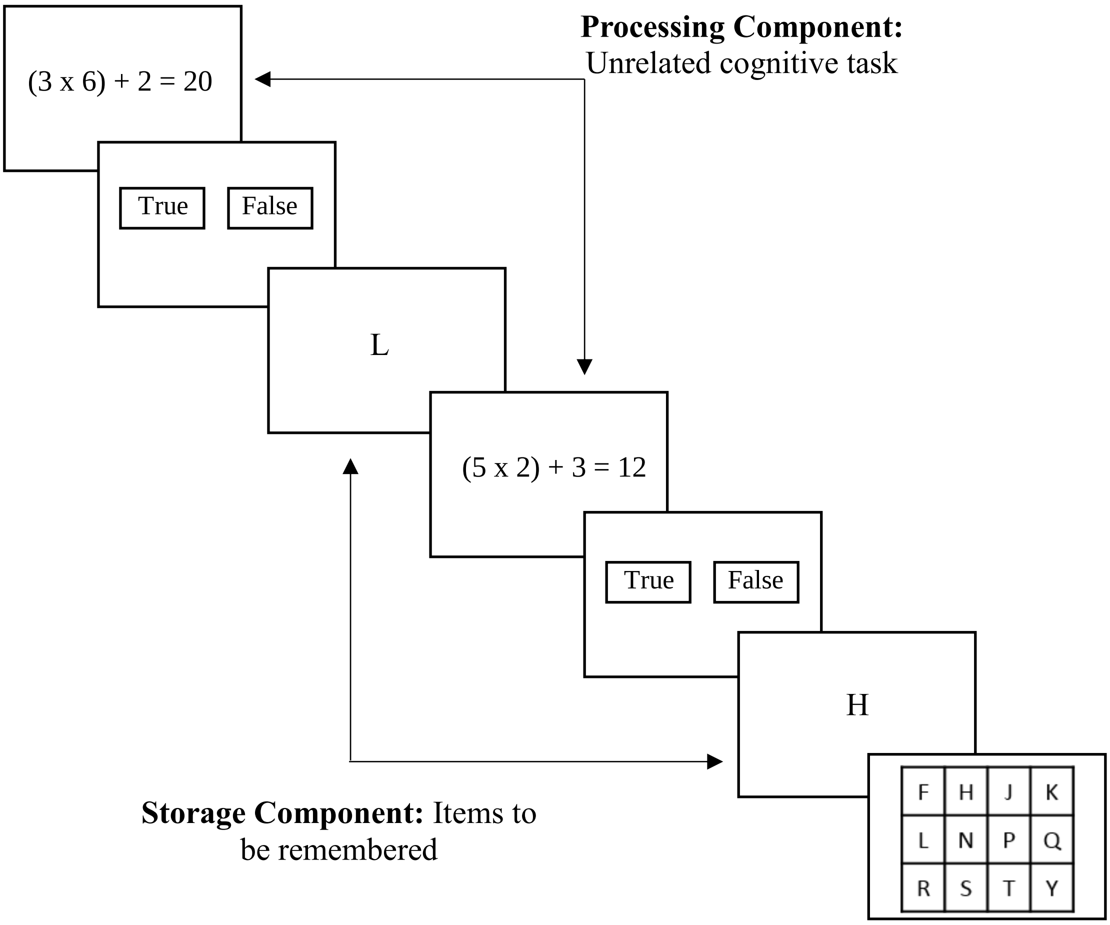


Figure 4. A visual depiction of the operation span task. This is one of the most commonly used complex span tasks. Participants are presented with letters that must be remembered, however in between each letter is a math problem. Participants must indicate whether the answer to the math problem is true or false before they are presented with another letter. After a series of such trials, a grid is presented and participants must select all the letter that had been presented in the correct order. All complex span tasks share this structure with processing and storage components interleaved throughout each block.

Performance on these complex span tasks show moderate to high correlations, providing support that they are all measuring a similar underlying construct (Conway et al., 2005; Kane et al., 2004; Unsworth et al., 2009). Although there are a variety of other ways to measure the construct of working memory, this thesis will focus specifically on complex span measures of WMC given their wide use, and the important role that executive attentional control processes have been proposed to play in performance on these tasks (Kane, Conway, et al., 2007). Such executive control processes also play a crucial role in task switching, so an examination of the relationship between performance of these two tasks is an interesting avenue for further research.

1.3.2 Theoretical accounts of working memory.

While the multiple components model (Baddeley & Hitch, 1974) was one of the first models to attempt an explanation of working memory, a multitude of other models have emerged over the years (Miyake & Shah, 1999). This section will not constitute an exhaustive review of such models, but will instead focus on theories that have the strongest bearing on the investigation of the relationship between task switching and WMC. This will begin with a discussion of working memory models that stress the importance of attention, followed by those that stress the importance of task switching in working memory.

1.3.2.1 Models of working memory that stress the importance of attention.

Although some models of working memory, including the multiple components model have argued that working memory and LTM are distinct structures (Baddeley & Hitch, 1974; Kieras, Meyer, Mueller, & Seymour, 1999; Towse & Hitch, 2007; Vandierendonck, 2016), others have suggested that working memory is not a separate structure, but is just the activated part of LTM (Cowan, 1988; Lovett et al., 2000; Oberauer, 2009). One such theory is the embedded processes model of working memory (Cowan, 1988, 1995, 1999, 2008; Cowan et al., 2005). According to this model, information held in working memory represents the subset of currently activated

LTM that is in the focus of awareness, and that attention is directed to. The central executive controls the focus of attention and this is how working memory is regulated (Cowan, 1999). The activated information that is in the focus of attention is limited in capacity to approximately four chunks of information, and is subject to decay with time (Cowan, 2001, 2008). This model is not entirely dissimilar to the multiple components model, and it has been suggested that the differences are primarily with regards to which aspects of the system are emphasized (Baddeley, 2012). The embedded process model clearly emphasizes the role of a limited capacity central executive, and stresses the importance of attention (Cowan, 1999), while the multiple components model focusses more on the limited capacity storage units (Baddeley & Hitch, 1974).

Oberauer’s model shares many of the tenets of the embedded process model, including the view that working memory is the portion of LTM that is activated, and the emphasis on the importance of attention (Oberauer, 2009; Oberauer, Suss, Wilhelm, & Sander, 2007). It extends Cowan’s (1999) model by further defining the features of working memory. It breaks working memory into a system with two parts; declarative and procedural. Declarative working memory makes particular representations available for processing by determining the relevant memory contents, and procedural working memory does the actual processing that is necessary for a particular goal. Declarative working memory consists of three components; an activated part of LTM, a component called the region of direct access, which is responsible for integrating and binding information from LTM into a multidimensional system where it can be processed and manipulated, and finally the focus of attention, which is responsible for selecting the target for processing. Procedural working memory has three analogous components, including the bridge, which holds the current task set in mind. This area, like the region of direct access creates and holds bindings between representations to form task sets.

Procedural working memory is the closest relative to the central executive of the multiple components model (Baddeley & Hitch, 1974). This model is less about memory, and more about describing an attentional system that deals both with perception and LTM to perform complex cognitive activities (Oberauer, 2009). The capacity limit of working memory is not due to the focus of attention, as suggested by the embedded process theory (Cowan, 1999), but instead is thought to be due to limits in the ability to bind information together in the region of direct access (Oberauer et al., 2007). The focus of attention is instead limited to a single element, rather than four chunks as suggested by Cowan (2001). Like the embedded process model, this working memory theory moves away from a focus on memory structure which was fundamental to the multicomponent model of working memory and instead focusses on function and the important role of attentional processes.

The ACT-R model of working memory (Anderson et al., 1996; Lovett et al., 2000) also shares similarities with the embedded process theory (Cowan, 1999) and Oberauer’s (2009) model. This theory also distinguishes between declarative and procedural memory, and suggests that working memory is merely the portion of declarative memory that is active above a certain threshold. The more active that a chunk is in declarative memory, the more likely that it will be used by procedural memory in the performance of a task. This activity level is dependent on source activation which the chunk receives from attention. Like the embedded processes theory, the ACT-R model suggests that WMC is limited because source activation has limits; there is a limited amount of attention to be distributed (Anderson et al., 1996). The amount of source activation available differs between individuals and this helps to explain individual differences in WMC (Lovett et al., 2000). This ACT-R model again stresses the importance of attention in WMC, rather than the importance of the size of specific storage units.

These three models of working memory place a great deal of emphasis on the role of attentional processes in working memory. They redirect the focus away from discussing how many units can be stored and instead focus on how much can be attended to. Task switching also requires attentional control to focus on the correct aspect of the bivalent stimulus on any given trial. While these models stress the role of attentional focus, other working memory models actually stress the importance of task switching in working memory and we will now turn our focus to such models.

1.3.2.2 Models of working memory that stress the importance of task switching.

The task-switching model of working memory is in line with the multiple components model (Baddeley & Hitch, 1974) in suggesting that working memory is a multicomponent system with a limited capacity (Towse & Hitch, 1995, 2007; Towse, Hitch, & Hutton, 2000). Rather than emphasizing a resource-sharing model in which resources are shared between processing and storage, the task-switching model proposes a switching mechanism. The model suggests that at any given moment during a working memory task, participants are either performing the cognitive task, or remembering their items, but not doing both. Instead, they switch between the two tasks of processing and storage. This model stresses time-based forgetting with limits in WMC reflecting forgetting due to the time spent performing the processing task.

The time-based resources sharing model of working memory also emphasizes the importance of switching between storage and processing tasks (Barrouillet, Bernardin, & Camos, 2004). This model focusses on the role of attention in working memory and assumes that both processing and storage require attention so they must compete for it as it is a limited resource. When attention is switched away from the storage task, memory decay will begin, and the memory trace will need to be refreshed by refocusing attention. Attention is shared by rapidly and frequently switching attention between processing and storage. This heavy emphasis on attention is similar to the models previously discussed (Cowan, 1999; Lovett et al., 2000; Oberauer, 2009). The difference between this model and the task-switching model is that while the switching model (Towse & Hitch, 1995) suggests that switches take place in between the processing and memory tasks, whenever a new to-be-remembered item is presented, the time-based resources sharing model suggests that switches are far more rapid and frequent and occur throughout the task. Switching is not restricted to when a new memory item is presented. Instead, when completing the processing task (e.g. math problems), participants may take brief moments while doing the math to briefly and rapidly switch their attention to the memory task to reactive the memory. Both the task switching model and the time-based resources sharing model of working memory emphasize the importance of effective switching abilities to allow for switching between storage and processing during WMC tasks.

A new model has recently been proposed which draws inspiration not only from previous working memory models, but also from the task switching and dual task literature (Vandierendonck, 2016). This model draws heavily on the multicomponent model of working memory (Baddeley, 2000), and retains what it considers to be the most useful aspects of this theory. Vandierendonck’s (2016) model retains the phonological loop, visuospatial sketchpad, and the episodic buffer. It eliminates the central executive and instead replaces it with three components, the first of which is a passive executive memory component. This is a storage area which is responsible for maintaining task sets including sets that are currently active and those that were recently relevant. It holds memory traces of the goal that is currently being performed and interacts heavily with LTM, the episodic buffer, and the phonological loop in order to do so. Although this executive storage has a limited capacity, it can certainly hold multiple task sets active at any given time. This component is similar to the procedural working memory construct suggested by Oberauer (2009).

Even though the executive memory component is merely a passive storage component, this model does include executive control. It proposes a distributed procedural knowledge network comprised of a knowledge base, which contains a collection of acquired procedural rules, and a processing engine. The engine selects and executes rules from the knowledge network that match the contents of working memory.

This model is consistent with the task-switching model (Towse & Hitch, 1995, 2007) and the time-based resources sharing model (Barrouillet et al., 2004) as it suggests that switching between memory storage and task processing is necessary when performing a working memory task, and it likely incurs a switch cost (Vandierendonck, 2012, 2016). One aspect of Vandierendonck's (2016) model that is particularly interesting is that even though it is a model designed to explain working memory, it has also been used to account for performance in switching tasks. This model proposes an important link between working memory and task switching, suggesting that working memory plays a role in switching as it provides facilities to maintain and implement task sets and guide goal selection. However, despite this proposed link, this model does not imply a relationship between working memory and task switching performance. Instead, it suggests that working memory and switching tasks may not draw on the same limited capacity resource. Different resources may be used for the maintenance of information in working memory and the control processes used by task switching. Nonetheless, an interesting link between these two processes is put forth by this model.

Each of these models suggest that switching between processing and storage tasks represents an important feature of working memory performance (Barrouillet et al., 2004; Towse & Hitch, 1995; Vandierendonck, 2016). The idea that a single memory model can account for the findings from both working memory and task switching studies points to the need for further research to establish the relationship between performance on these tasks more clearly. We will now turn to the discussion of a final working memory model which emerged out of research with the complex span tasks discussed earlier.

1.3.2.3 Individual differences in working memory capacity.

One of the most prominent models of individual differences in WMC is the executive attention theory of WMC (Engle, 2001, 2002; Engle & Kane, 2004; Kane, Conway, et al., 2007). This theory is of importance as it makes specific predictions about the potential relationship between WMC and task switching. Like many of the models mentioned earlier (Cowan, 1999; Lovett et al., 2000; Oberauer, 2009), the executive attention theory suggests that short term memory is just the portion of LTM that is above a certain threshold. It also stresses the importance of attention, suggesting that working memory is located at the intersection of attention and memory (Meier & Kane, 2017). Information stored in short term memory is subject to loss due to decay or interference, but can be maintained using attention. Executive control processes can also be used to keep a particular area of LTM activated or to re-retrieve information that was lost over time. According to this model, WMC is an attentional control process that allows us to maintain information in active states outside of conscious awareness (Kane, Conway, et al., 2007). WMC does not tell us about how many items one can store in some area. Instead, it tells us about individual differences in executive attentional control, which is important in maintaining information in an active state, especially when conflict and interference are present (Engle, 2001, 2002; Engle & Kane, 2004).

The main tenet of the executive attention theory is that individual differences in WMC are driven by differences in executive attentional control processes (Kane, Conway, et al., 2007). Support for this model comes from research showing that WMC is predictive of a range of higher-order cognitive functions and is highly associated with a number of attentional control tasks that do not have a memory component (Meier & Kane, 2017). WMC as assessed by complex span tasks is strongly associated with fluid intelligence (Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004), reading comprehension (Daneman & Carpenter, 1980; Daneman & Merikle, 1996; Engle, Carullo, & Collins, 1991; McVay & Kane, 2012b; Turner & Engle, 1989), and verbal scholastic aptitude test scores (Conway & Engle, 1996; Daneman & Carpenter, 1980). In addition to these higher order cognitive tasks, WMC is also related to performance on a number of attentional control tasks including the dichotic listening task (Conway, Cowan, & Bunting, 2001; Furley & Memmert, 2012), the Stroop task (Kane & Engle, 2003; Unsworth, Redick, Spillers, & Brewer, 2012), the anti-saccade task (Kane, Bleckley, Conway, & Engle, 2001; Luo, Zhang, & Wang, 2017; Meier, Smeekens, Silvia, Kwapil, & Kane, 2018; Unsworth et al., 2012), the flanker task (Unsworth et al., 2012), and the go/no-go task (McVay & Kane, 2009b). Additionally, WMC has been associated with a number of real-world activities requiring attentional control, including following directions (Engle et al., 1991), making tactical decisions (Furley & Memmert, 2012), and mind wandering (McVay & Kane, 2009b, 2012b).

Across these studies, high WMC participants are consistently found to display superior attentional control abilities. For example, in a study examining performance on an antisaccade task, participants completed both prosaccade and antisaccade conditions. In the pro-saccade condition, participants were visually cued to a target location and had to press a key corresponding to the target as rapidly as possible. In the antisaccade condition, the cue appeared in the opposite location to where the target would appear. Although high and low spans performed similarly in the prosaccade condition, suggesting comparable automatic orienting abilities, differences emerged in the antisaccade condition where attentional control was required. High WMC participants were faster and more accurate on antisaccade trials, suggesting that they are better able to control their attention (Kane et al., 2001).

These results all support the executive attention theory, pointing towards the importance of executive attentional control processes in WMC task performance. However, one anomaly that stands out from these confirmatory results is that of task switching. Task switching is one of the only attentional control tasks that was not found to be correlated with performance on tasks of WMC (Kane et al., 2003; Kane, Conway, et al., 2007). This is problematic for the executive attention theory as the key component to performance on task switching is executive attentional control. Most of the task switching theories suggest that such endogenous attentional control processes are important in explaining switch costs (Meiran, 1996; Rogers & Monsell, 1995; Sohn & Anderson, 2001). To explore this anomalous finding further, the next section will review research which has directly examined the association between task switching and WMC.

1.4 Exploring the Relationship between Working Memory Capacity and Task Switching

There are a number of reasons to expect that scores on complex span WMC tasks should be related to scores on task switching tasks. These tasks are both thought to tap executive functions and a number of theories seem to suggest that they may share similar underlying cognitive processes. Both of these tasks appear to recruit similar brain regions during performance, providing additional support for the idea that performance on these tasks requires the use of similar cognitive operations. This evidence will be explored here, followed by an examination of research which has assessed their association.

1.4.1 Theoretical arguments for an association.

A number of the working memory theories just discussed suggest that task switching plays an important role in working memory functioning. In the multiple component model of working memory, one of the major functions of the central executive is proposed to be the ability to effectively switch between tasks (Baddeley, 1996, 2002; Baddeley, Chincotta, & Adlam, 2001). Several theories which also subscribe to the multicomponent model have emphasized the importance of the ability to effectively switch between the performing of process and storage tasks as an important factor in performance on WMC tasks (Barrouillet et al., 2004; Towse & Hitch, 1995, 2007; Vandierendonck, 2016). In line with these working memory theories, there are task switching theories that suggest that working memory abilities explain a large portion of switch costs, with working memory mediating task-set reconfiguration (Mayr & Kliegl, 2000, 2003; Sohn & Anderson, 2001). In addition to playing a role in explaining switch costs, it has also been proposed that working memory plays an important role in congruency effects observed in task switching (Meiran & Kessler, 2008). These theories suggest an important relationship between working memory and task switching.

Although the majority of theories suggest that task switching and WMC share an important relationship, it is important to note that not all theories share this viewpoint. Others have argued that working memory should be treated as a completely separate construct from other executive functioning abilities, stressing that it is not necessary for WMC to be related to task switching (Oberauer et al., 2007). Oberauer (2009) has suggested that in the performance of switching tasks, high WMC may not necessarily be helpful. It is proposed that switch costs result from the time required to switch task sets in the bridge in procedural working memory. The bridge can only hold one task set at a time, so when the task set switches, the new task set must be retrieved from LTM and the old task set must be removed from the bridge. People with high WMC would find it difficult to remove the current task set from the bridge due to strong bindings, but they would be better at strongly binding the new task set once the old set had been removed. In contrast, those with low WMC would have weaker bindings, so they would be able to remove the old task set easily, but the new task set would not be very strongly bound. According to this model, similar performance would be expected on switching tasks because those with both high and low WMC would have disadvantages (Oberauer, 2009). Others have also suggested that task switching and WMC may not share the same set of resources (Logan, 2004; Vandierendonck, 2016). So, while the majority of the theoretical work in task switching and WMC suggests that performance on these two tasks should be related, that viewpoint is not universal. Clearly more work is needed to elucidate the true nature of this relationship.

1.4.2 The cognitive neuroscience of working memory capacity and task switching.

Working memory and task switching are two core executive functions (Diamond, 2013). All executive functions seem to involve a similar set of brain regions during task performance. A meta-analysis of 193 neuroimaging studies which used a range of executive function measures including working memory and switching tasks, among others, found that a network of frontal and parietal regions was consistently activated across all of the executive function domains examined. This network of regions included the anterior cingulate cortex and dorsolateral prefrontal cortex (DLPFC) in the frontal lobes, and clusters of activation that spanned both the inferior and superior parietal lobe (Niendam et al., 2012). This network of fronto-parietal regions is known as the cognitive control network (Cole & Schneider, 2007) and is consistently activated across a range of executive functioning tasks (Collette et al., 2005; Derrfuss, Brass, & von Cramon, 2004).

This fronto-parietal network plays an important role in the performance of complex span tasks (Osaka & Osaka, 2007). Compared to the performance of a simple arithmetic task, performance on the operation span task has been associated with activity in a range of frontal and parietal regions including the anterior cingulate cortex, DLPFC, and the superior and inferior parietal lobule (Faraco et al., 2011; Kondo, Morishita, et al., 2004). Similarly, the reading span task has been associated with activity in the anterior cingulate cortex, inferior frontal gyrus and superior parietal lobule (Osaka et al., 2004).

The neural basis of individual differences in WMC has also been explored. Across a range of complex span tasks, variations in activity in the DLPFC and anterior cingulate cortex have been observed between those with high and low WMC.

Functional connectivity analyses have shown that activity in the anterior cingulate cortex and DLPFC is more highly correlated in participants with high WMC than those with low WMC in both the reading span (Osaka et al., 2004) and the listening span tasks (Osaka et al., 2003). Effective connectivity from the anterior cingulate cortex to the DLPFC has been found in high WMC participants, but not in low WMC participants in both the operation span task (Kondo, Morishita, et al., 2004) and the spatial span task (Kondo, Osaka, & Osaka, 2004). These studies have shown that despite differences in modality, performance on working memory span tasks consistently activate the fronto-parietal cognitive control network. Additionally, the relationship between activity in the anterior cingulate cortex and DLPFC appears to offer some explanations regarding differences in performance on span tasks.

The DLPFC has been implicated in attentional maintenance (Kane & Engle, 2002), the anterior cingulate cortex is thought to be involved in conflict monitoring (Botvinick, Braver, Barch, Carter, & Cohen, 2001), and the superior parietal lobule is thought to play an important role in attentional focusing (Osaka & Osaka, 2007). These are all important components of executive function, and the studies described suggest that these regions all work together during the completion of complex span WMC tasks. High spans show better connectivity between the anterior cingulate cortex and DLPFC (Kondo, Morishita, et al., 2004; Kondo, Osaka, et al., 2004; Osaka et al., 2003; Osaka et al., 2004), suggesting that those with high WMC may have a superior attentional control system. These findings fit well with the executive attention theory of WMC which emphasizes the importance of executive attentional control in WMC (Kane, Conway, et al., 2007). This theory has also stressed the importance of DLPFC functioning in the performance of complex span tasks, due to its role in the maintenance of information in the face of conflict (Kane & Engle, 2002).

Performance on task switching tasks is also associated with activation of the fronto-parietal network (Braver, Reynolds, & Donaldson, 2003; Dajani & Uddin, 2015; Karayanidis et al., 2010; Kim, Cilles, Johnson, & Gold, 2012; Richter & Yeung, 2014; Ruge, Jamadar, Zimmermann, & Karayanidis, 2013; Wager, Jonides, & Reading, 2004). A recent meta-analysis of 34 fMRI studies of task switching showed that compared to trials in which participants repeat a task, switch trials are associated with activity in a variety of primarily left-lateralized frontal and parietal regions (Richter & Yeung, 2014). Although there is some variability, most task switching studies report consistent activation associated with switching in the DLPFC, the ventrolateral PFC, the pre-supplementary motor area, the anterior cingulate cortex, and both superior and inferior parietal cortex (Karayanidis et al., 2010). These regions are similar to those reported in the neuroimaging literature on WMC.

One study has actually compared regions elicited from a meta-analysis of task switching studies to brain regions that were found to be activated in a meta-analysis of complex span tasks and found a great deal of overlap in the neural regions activated for these tasks (Wager et al., 2004). Given that these tasks share underlying neural substrates, we may expect that performance on these two tasks would be highly related. We will explore this proposition now.

1.4.3 Research on the association between working memory capacity and task switching.

WMC and task switching have been widely studied independently however, there has been comparatively little research done examining the association between these two important constructs (Liefooghe, Barrouillet, Vandierendonck, & Camos, 2008; Vandierendonck, 2016). This research falls into four different categories. We will first discuss studies that have examined the impact of articulatory suppression on task switching in an attempt to explore the role of the phonological loop in switching performance. Studies on the role of task switching load in working memory tasks and on working memory load during switching tasks will then be explored. We will also explore whether a relationship exists between WMC and a closely related construct to task switching; multitasking. Finally, we will examine previous research which has directly examined the association between task switching and WMC performance.

1.4.3.1 The role of the phonological loop in task switching.

A number of studies have shown that taxing verbal working memory using articulatory suppression has an effect on switch costs (Baddeley et al., 2001; Emerson & Miyake, 2003; Miyake, Emerson, Padilla, & Ahn, 2004; Saeki & Saito, 2004). The first study to examine the role of the phonological loop in switching used the list paradigm and found that switch costs were increased when a verbal task was performed alongside the switching task (Baddeley et al., 2001). When a complex verbal trails task was performed concurrently with the list paradigm, switch costs were increased both when cues indicating the task to be performed were present and when they were absent. In contrast, a less complex articulatory suppression task which involved repeating the days of the week or months of the year led to an increase in switch costs only when cues were absent. The results suggest a role for the central executive in switching even when cues are present and point to the important role of the phonological loop in maintaining the switching program when cues are absent. When there are no cues available to guide performance, it appears that verbalizing the switching program in the phonological loop is of paramount importance, and preventing this through articulatory suppression has a large impact on switch costs (Baddeley et al., 2001).

This finding was later replicated in a study which had participants repeat A-B-C while performing a switching task (Emerson & Miyake, 2003). Once again, adding cues to the switching task led to a significant reduction in the effect of articulatory suppression on switch costs. The authors suggest that the utilization of verbal self-instruction is necessary to update task sets in working memory (Emerson & Miyake, 2003). These findings have been further replicated in another study using the list paradigm (Saeki & Saito, 2004) and have even been extended to the explicitly cued task switching paradigm (Miyake et al., 2004). Taxing verbal working memory using articulatory suppression has also been shown to influence task choice on the VTS paradigm, leading to more repetitive responding (Weywadt & Butler, 2013). These studies all highlight a potentially important role for verbal working memory in task switching performance under certain circumstances.

1.4.3.2 Working memory load and switch costs.

Another approach to examining the relationship between working memory and switch costs is to determine how the effects of additional load impact performance. This approach allows us to examine whether the two tasks share the same resources. Logan (2004) created the task span procedure to examine whether working memory and task switching share a common set of resources. In the task span procedure, participants are required to memorize a list of task names which are presented in a particular order. Following this, they are presented with a series of stimuli on which to perform those tasks. Based on the memorized cue order, at times participants repeat the same task, and other times they switch between the tasks. No cues accompany the actual stimuli. The stimuli are always digits (e.g., 3 or three), and the task names include high-low, odd-even, or digit-word specifying whether participants should perform the magnitude, parity, or form task on a given trial (See Figure 3).

The main dependent variable on the task span procedure is the number of tasks performed correctly in order. In addition to assessing task span, traditional memory span can also be measured based on the recall of the task names without the requirement to then perform the tasks (Logan, 2004). Using this paradigm, Logan (2004) found that spans measured using the traditional memory span task did not differ from task spans. Even when the number of task switches within a list were manipulated, spans remained comparable, suggesting that task switching and working memory tasks do not share a single set of resources. Having to perform the switching task did not impact performance on the memory portion of the task. This study also found that task span did not correlate with switch costs, further suggesting a lack of association between memory storage and task switching (Logan, 2004). Another study that combined working memory and task switching in the same task also found that switch costs within the combined task were not related to working memory capacity (Unsworth & Engle, 2008), further suggesting a lack of relationship between these constructs.

In contrast, other studies have suggested that working memory and task switching may share some resources. One study used a combined task switching and continuous span task. They had participants complete a variation of the list paradigm will simultaneously completing a continuous span task involving the presentation of 3-6 consonants which needed to be remembered (Liefooghe et al., 2008). After each consonant was presented, a series of eight numbers appeared in red or blue, with the colour indicating the task to be performed, either magnitude or parity. Pure lists were either all blue or all red, requiring the performance of a single task, while alternating lists were a mixture of blue and red digits, requiring subjects to switch between the parity and magnitude task. Results indicated that recall of the consonants was much worse in the alternating lists condition, suggesting that task switching actually did have an impact on working memory performance (Liefooghe et al., 2008).

As mentioned earlier, the list paradigm has some confounds with regards to working memory load, so, Liefooghe et al. (2008) repeated the experiment described above using lists that all involved switching, with the lists differing with regard to the number of switches required. Working memory recall was worse on lists requiring more switches, providing further support for the idea that task switching load impairs the ability to hold information in working memory. In contrast, switch costs themselves were not affected by memory load. The switch cost remained the same, even when the number of consonants to recall increased (Liefooghe et al., 2008). The results of this study suggest that task switching and working memory may share some common capacity, although clearly their relationship is complex, with switching load impacting working memory performance, but working memory load having little impact on switch costs.

Another study investigating this same question used a very different task and once again elicited quite different results with regards to the impact of working memory load on switch costs (Souza, Oberauer, Gade, & Druey, 2012). In this study, on any one run of trials, participants were required to learn between 1 and 3 number sets and to perform between 1 and 3 tasks on those numbers. The tasks involved indicating whether a number was smaller or larger than 5, even versus odd, or outer versus inner, indicating whether the target was located on the outer or inner positions of a number line from 1 to 9. Arbitrary task cues were used to cue the tasks. During a run both tasks and number lists could switch thus task switch and list switch costs could be calculated. On a trial, the vertical position of the cue indicated which number list to call from memory and the horizontal position indicated which number within the list to perform the cued task on. Using this complex paradigm, this study found that task switching costs increased when 3 lists needed to be held in working memory as compared to when only 1 or 2 number lists were required. With increasing working memory load, switch costs increased, which is the opposite of what was found in a previous study (Liefooghe et al., 2008). The authors suggest that their results may be due to articulatory suppression (Souza et al., 2012). When three lists had to be maintained, participants may have needed articulatory rehearsal to remember the lists, and this would then increase switch costs as suggested by previous studies (Baddeley et al., 2001).

There is clearly some ambiguity in the results from studies examining the influence of increasing load on performance in working memory and task switching. Although some studies have suggested that task switching and working memory are completely independent, and do not share resources (Logan, 2004), others have found that increasing switching load can decrease working memory performance (Liefooghe et al., 2008) and increasing working memory load can increase switch costs (Hester & Garavan, 2005; Souza et al., 2012), although the opposite has also been shown (Liefooghe et al., 2008). Further studies are needed to clarify this area of research, but there does seem to be some indication that working memory and task switching may share some resources.

1.4.3.3 Working memory capacity and multitasking.

A close construct to task switching is multitasking. Multitasking is a difficult concept to define, but a broad definition of the term is that we are multitasking any time we complete multiple tasks at the same time (Koch et al., 2018; Strobach, Wendt, & Janczyk, 2018). Multitasking can be studied in a multitude of ways. Dual-task paradigms can be used to examine multitasking when tasks must be completed simultaneously and task switching paradigms can be used to explore how we complete multiple tasks in a more sequential manner (Koch et al., 2018; Strobach et al., 2018). Multitasking has also been studied using real-world situations that require the juggling of multiple tasks, such as cooking a virtual breakfast (Pollard & Courage, 2017). Given the close relationship between the constructs of multitasking and task switching, it is useful to explore whether multitasking abilities are linked to WMC.

A wide variety of studies have shown that multitasking abilities are related to WMC, as measured by complex span tasks including the operation span (Hambrick, Oswald, Darowski, Rench, & Brou, 2010; Liu, Wadeson, Kim, & Nam, 2016; Pollard & Courage, 2017), reading span (Konig, Buhner, & Murling, 2005; Redick, 2016), symmetry task (Hambrick et al., 2010), and computation span tasks (Colom, Martínez-Molina, Shih, & Santacreu, 2010). Higher WMC is associated with better multitasking. These studies have used a wide variety of tasks to measure multitasking abilities. Most of the tasks have been designed to simulate real world scenarios, such as the virtual breakfast task (Pollard & Courage, 2017) and the SynWin (Konig et al., 2005; Redick, 2016). The SynWin involves completing four sub-tasks including a recognition memory task, an arithmetic task, as well as visual, and auditory monitoring tasks. After practicing these subtasks on their own, participants must complete them all simultaneously as is often the case in various occupations. Other studies used tasks that resembled those completed by aircraft crew members (Liu et al., 2016) or that involved divided attention between various streams of information (Colom et al., 2010; Pollard & Courage, 2017). Despite the variation in their operational definitions of multitasking, these studies consistently found that WMC predicted multitasking performance, suggesting an important relationship between these constructs. Since task switching performance is considered an index of multitasking abilities (Koch et al., 2018), one would also expect to find a relationship between WMC and task switching. We will now turn our attention to studies that have specifically examined this question.

1.4.3.4 The association between performance on task switching and working memory capacity tasks.

The majority of studies that have directly examined the association between task switching and WMC as measured by complex span tasks have failed to find a significant relationship between performance on these tasks (Hambrick & Altmann, 2015; Kane et al., 2003; Kane, Conway, et al., 2007; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003). In an attempt to test the executive attention theory of WMC, a series of switching experiments were conducted to see if switch costs differed between those with high and low WMC (Kane et al., 2003; Kane, Conway, et al., 2007). Four different versions of the alternating runs paradigm with the number-letter task were used, with each version differing in regard to task cuing and response mapping details. Switch costs did not differ between high and low spans on any version of the alternating runs paradigm. These results are described briefly in a book chapter (Kane, Conway, et al., 2007) but were never published in detail, so the specific details of the experiments with regard to timing and cuing within the alternating runs paradigm are somewhat unclear, and it is not clear which span task was used to designate participants into high and low WMC. In any case, these initial results suggest that task switching as assessed by the traditional alternating runs paradigm is not related to WMC scores.

Another study attempting to explore the unity and diversity of the three most widely studied executive functions, switching, working memory, and inhibition also failed to find a relationship between task switching and WMC (Miyake et al., 2000).

They compared performance on the operation span task with performance on three switching tasks. The first switching task, the plus-minus task used the traditional list paradigm, the second task, used the traditional alternating runs paradigm with the number-letter task, and the third switching task was a cued local-global task. This task involved the presentation of a geometric figure on each trial in black or blue. The stimulus was a global figure (e.g., a triangle) that was composed of smaller local figures (e.g., many squares). The colour of the figure instructed participants whether to perform the local task or the global task. The local task involved vocally reporting the number of lines in the local figure while the global task involved reporting the number of lines in the global figure (1 line for a circle, 2 for an X, 3 for a triangle or 4 for a square). Half of the trials required participants to switch between the tasks, and half involved repeating the previous task. This task resembled the cued task switching paradigm as switch and repeat trials were randomized, however the cue was not presented before the stimulus, thus no preparation could take place. No significant correlations were found between operation span scores and switch costs on any of the switching paradigms (Miyake et al., 2000). These results were later replicated with similar switching paradigms (Klauer et al., 2010).

Null findings have also been found using four versions of the alternating runs paradigm with differing stimuli (Oberauer et al., 2003), and in a study which used a variant of the cued switching paradigm (Hambrick & Altmann, 2015). Hambrick and Altmann (2015) used a switching task that did not present a cue on every trial. Instead, the cue was presented at the beginning of a run of trials that required participants to perform the same task. So, switch cost was not calculated by comparing switch and repeat trials, but instead by comparing the first trial on a switch run with the first trial on repeat runs. Once again, in this study, task switching did not correlate with WMC

(Hambrick & Altmann, 2015). There has been one study using the alternating runs paradigm which found a relationship between switch costs and WMC in a sample of older adults, however this same study failed to find such a relationship in a group of young adults. These findings further suggests that in young adults there is no relationship between switching and WMC, but it also suggests that age may potentially play a role in this relationship (Gamboz, Borella, & Brandimonte, 2009).

From the evidence thus far, it is difficult to make any strong conclusions about the relationship between WMC and task switching. The studies described have used a variety of switching tasks including the list paradigm, the alternating runs paradigm, and variations on the cued switching paradigm in which the cue is presented simultaneously with the stimulus or at the beginning of a run of trials, and have consistently found null results. However, these findings don't necessarily mean that these two constructs are not related under any circumstances. It is possible that the amount of environmental support available to participants on the switching task (in the form of cues and instructions), or the amount of time participants have to prepare before switching may have an influence on this relationship. It is also possible that the approach to scoring on the task switching paradigms may have an impact on the relationship between WMC and switch costs. We will now turn our attention to these ideas.

One study has been completed to examine the relationship between WMC and switch costs in a situation with little environmental support. This study used the VTS paradigm and found a significant relationship between WMC and switch costs (Butler, Arrington, & Weywadt, 2011). The stimuli used were digits, and participants could choose whether to do the parity or magnitude task on each trial. There was little environmental support available as participants were not told what to do on each trial, instead they had to choose which task to perform on each trial. This study also manipulated the response-to-stimulus (RSI) interval between 100 ms and 1300 ms, varying the amount of time participants had between stimulus presentations. Results showed that WMC was correlated with switch costs, with higher switch costs associated with lower WMC, but only when RSI was kept short (Butler et al., 2011). When the switching task was especially difficult because there was a lack of time to prepare before each trial, switch costs were related to WMC. The results of this study highlight the important role that timing parameters play in the relationship between WMC and switching. Given that none of the studies that failed to find a relationship between these constructs appear to have manipulated the time available between trials (Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003), this may be one factor that could explain why they did not find the expected association between switching and WMC.

Recently, it has been suggested that traditional scoring of the switching tasks by calculating reaction time switch costs may be less than optimal (Hughes, Linck, Bowles, Koeth, & Bunting, 2014). Such an approach leaves out an important component of task switching performance; accuracy. By only examining reaction time, large variations in accuracy can be overlooked, and such information is likely to be meaningful for explaining task performance (Draheim, Hicks, & Engle, 2016). Another criticism of the traditional scoring method is that it uses difference scores. Switch costs are calculated as the difference in reaction time between switch trials and repeat trials. Difference scores tend to have low reliability (Draheim et al., 2016; Edwards, 2001; Hedge, Powell, & Sumner, 2018; Miller & Ulrich, 2013; Paap & Sawi, 2016). It has been suggested that given these flaws in the traditional scoring of task switching, a combined reaction time and accuracy scoring system would be beneficial and a variety of alternative scoring options with increased reliability have been proposed (Hughes et al., 2014).

To examine whether the traditional switch cost scoring method is to blame for the lack of relationship between WMC and switch costs, Draheim et al. (2016) examined whether the relationship would change if a different analysis technique was used. Participants completed a series of complex span tasks and two switching tasks, category switch and letter-number switch. When traditional difference score switch cost analyses were used, they found a significant relationship between WMC and switch costs. However, it was in the opposite direction to what would be expected. Those with low WMC also showed lower switch costs, indicative of better switching performance ($r = .26$, $p < .001$). This was an unexpected finding, so the authors proceeded to analyse the data using a bin scoring method which combined reaction time and accuracy. When the data was re-analysed, they found an even stronger relationship between WMC and task switching, and this time it was in the hypothesized direction ($r = -.49$, $p < .001$) with high WMC participants performing best on the switching task. Further supporting their proposition that scoring approaches are behind previous failed attempts to find a relationship between WMC and switching, Draheim et al. (2016) reanalysed the data of Oberauer et al. (2003). You will recall from an earlier description that this study failed to find a relationship between switch costs and WMC using traditional scoring methods. However, when the data were re-analyzed using the bin scoring method which combined accuracy and reaction time, the expected correlation did become significant. These findings suggest that previous studies may have failed to find the expected relationship between WMC and switching because of their analyses techniques.

It is important to note that using a combined accuracy and reaction time measure does not seem to be the only key to unlocking the mystery surrounding the relationship between WMC and task switching. Another recent study used a combined accuracy and reaction time measure, rate residual scores (Hughes et al., 2014), to examine the relationship between WMC and switching (Pettigrew & Martin, 2016). Using a cued task switching paradigm with no timing manipulations, no significant relationship was found between WMC and switch costs, although the authors note that the effects were close to significance (*p* = .10). It seems that the analysis technique chosen to examine performance on the switching task is of great importance, but it seems that there are likely other factors at play that would be useful to examine more thoroughly before drawing any final conclusions about the relationship between WMC and task switching.

Overall, the literature that directly examines the relationship between WMC and task switching is mixed. Most studies have failed to find a relationship between WMC and switch costs. This is perplexing given all of the theoretical literature which suggests an important association between these two constructs. These findings are concerning as they challenge the theoretical propositions put forth by a variety of theories, especially the executive attention theory of WMC. There are a number of possibilities for why most of the literature has failed to find an association.

One possibility, based on the compound-cue retrieval account, is that task switching does not measure executive attentional control (Kane, Conway, et al., 2007; Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Schneider & Logan, 2005). If task switching does not actually tap into executive processing, then it should not be related to WMC and these results would not be a problem for the executive attention theory. However, numerous studies have shown that true task switch costs are still present even after cue switch costs are accounted for (Mayr, 2010; Mayr & Kliegl, 2003; Monsell & Mizon, 2006) and task switching is still considered an important measure of executive functioning (Diamond, 2013). Nonetheless, to rule this out, it will be important to consider the role of the cue in the association between WMC and task switching. This will be considered in Experiment 1 (Chapter 2) of this thesis as the association between task switching and WMC will be explored using a variety of cue types. This assertion will also be explored more thoroughly in Experiment 3 (Chapter 4) when the association between WMC and task switching are explored after the effects of cue switching are controlled for.

A second possibility is that it all comes down to the way that switch costs are scored. There is some promise for this as a relationship with WMC has been found when accuracy and reaction time measures are combined to measure task switching performance (Draheim et al., 2016). However, this has not been a universal finding, and others who have used the combined scoring methods have still failed to find a significant relationship between WMC and task switching (Pettigrew & Martin, 2016). To explore this in more depth, all three studies in this thesis will analyse the switching data in multiple ways including the traditional switch cost difference score method, the combined accuracy and reaction time method, as well as using a variability approach. Intraindividual variability in performance on cognitive control tasks has been proposed as a novel way of measuring executive control abilities (Kane et al., 2016; Unsworth, 2015). This multi-scoring approach will highlight whether the scoring method chosen has an important influence on the relationship between WMC and task switching.

Finally, it will be important to examine the task design circumstances under which task switching and WMC are related. It will be important to examine the role of timing in the relationship between WMC and task switching. The only study to manipulate timing did find a relationship between WMC and switch costs at one of their timing manipulations (Butler et al., 2011). They used the VTS, and manipulated RSI. No previous study has manipulated timing using the cued task switching paradigm and exploring the role of CSI to see whether controlled preparation time has an influence on the relationship between WMC and task switching. I will do this across all three studies presented in this thesis. All of the previous studies discussed above have used the same switch frequency of 50% despite previous research suggesting that keeping the probability of a task switch relatively low, at approximately 25% is most likely to encourage task-set reconfiguration processes (Monsell & Mizon, 2006). It is this task-set reconfiguration that we are most interested in measuring as it is the component of switch costs that we would expect to be related to WMC since it is thought to reflect executive attentional control. All three experiments described in this thesis will keep the switch probability low to encourage task-set reconfiguration.

At present, the association between WMC and task switching performance is ambiguous. The results are quite mixed. Are these tasks related? Do they measure a similar underlying construct? Further research is needed to determine under exactly which circumstances a relationship exists between task switching and WMC. That is the goal of the present thesis.

1.5 Outline of the Thesis

This thesis will explore the relationship between task switching and WMC in order to come to a conclusion about whether there is a relationship between these two constructs. A variety of task switching paradigms and analysis techniques will be used in an attempt to elucidate the circumstances under which they are related. Task switching and working memory are considered to be two of the core executive functions and it has been suggested that they both measure similar underlying cognitive processes, namely, endogenous executive attentional control. Given this, we would expect to find a relationship between performance on these tasks. If we are unable to consistently find such a relationship, it may have important implications for a number of theories of both task switching and WMC. It is imperative that we know what it is that these tasks are measuring given their pervasive use in the field of cognitive psychology.

Chapter 2 of this thesis will describe Experiment 1 which examines the relationship between WMC and task switching using three of the most widely used task switching paradigms. Each of the paradigms will differ with regard to the amount of cueing information provided to participants, and timing parameters will also be manipulated. A variety of analysis techniques will be used to explore performance on the switching task. This experiment provides information about whether paradigm specific differences underlie the ambiguous nature of previous results.

Chapter 3 will describe the results of Experiment 2, a replication and expansion of Experiment 1 with a larger sample. This experiment will explore the relationship between WMC and task switching separately for low and high WMC participants. Experiment 2 will also explore the role of task difficulty in the relationship between WMC and task switching.

Chapter 4 will describe Experiment 3 which explores the relationship between WMC and task switching when the effects of cue switch costs are controlled for. This Experiment will shed light on whether previous research may have failed to find an association between these tasks due to the confounding effects of cue switch costs. As with the earlier experiments, a variety of analysis techniques will be used to explore task switching performance.

Finally, Chapter 5 will integrate the findings of the three experiments described in this thesis. This final chapter will address methodological difficulties with this type of work and will provide some conclusions about the relationship between WMC and task switching.

Chapter 2 – Exploring the Relationship between Working Memory Capacity and Task Switching

2.1 Objective

The constructs of working memory capacity (WMC) and task switching are widely studied in cognitive psychology. However, the conclusion of research examining the association between these constructs remains unclear. Whether performance on these tasks is associated has important implications for a number of theories of both WMC and task switching. However, this area has been relatively under researched (Liefooghe et al., 2008; Vandierendonck, 2016). The executive attention theory holds that individual differences in WMC are primarily due to differences in executive attentional control processes (Kane, Conway, et al., 2007). This is supported by a range of research showing that WMC is associated with performance on a number of attentional control tasks that do not have a memory component (Conway et al., 2001; Kane et al., 2001; Kane & Engle, 2003). However, one anomaly that stands out is that of task switching. Task switching is one of the only attentional control tasks not found to correlate with WMC (Kane et al., 2003; Kane, Conway, et al., 2007).

Most studies that have directly examined the association between task switching and WMC using complex span tasks have not found a relationship between performance on these tasks (Hambrick & Altmann, 2015; Kane et al., 2003; Kane, Conway, et al., 2007; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003). These studies used the list paradigm (Klauer et al., 2010; Miyake et al., 2000), the alternating runs paradigm (Kane, Conway, et al., 2007; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003), a variation on the alternating runs paradigm in which cues are presented simultaneously with the stimulus (Klauer et al., 2010; Miyake et al., 2000), the explicitly cued switching paradigm (Pettigrew & Martin, 2016), or a variation of the cued paradigm (Hambrick & Altmann, 2015). Some studies suggested an association may exist when the right task switching paradigm is used to tap endogenous attentional control, such as the voluntary task switching paradigm (Butler et al., 2011), or when different analysis techniques are used to examine switch costs (Draheim et al., 2016).

The aim of the present study is to explore whether there is a relationship between WMC and task switching. This was examined using a variety of switching paradigms and analysis techniques to determine whether these methods of measurement and analysis have an influence on this relationship. Participants completed a standard WMC task and three different task switching paradigms. This study will provide a better understanding of the circumstances under which WMC and task switching are related.

2.1.1 The role of environmental support.

My first research question examines whether the relationship between WMC and switch costs changes based on the amount of environmental support available during task performance. Environmental support refers to the amount of information available in the environment to guide task responses directly. This is usually in the form of cues in the task switching paradigm. The amount of environmental support available should impact the amount of top-down executive control required for task performance (Arrington & Logan, 2005). WMC would only be related to switch costs if switch costs were indexing executive attentional control abilities. One argument for the lack of relationship between WMC and switching is that task switching does not require endogenous executive control processes (Kane, Conway, et al., 2007; Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010). According to the compound-cue retrieval model, when the explicitly cued task switching paradigm (See Chapter 1 for a description of this paradigm) is used, the environment provides you with all of the information needed to complete the task, so top-down control is not necessary. On this paradigm, participants create a compound of the explicit cue word and the stimulus and they use that compound to retrieve the correct response from LTM without the need for any kind of executive process (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010). Different switching paradigms likely recruit top-down executive attention resources to differing degrees. Paradigms with a lot of environmental support, like the cued task switching paradigm, will not require as much top-down control for task performance because performance can be guided by the environment. Paradigms with little environmental support should require a great deal of top-down control because there is not any information available in the environment to guide task performance (Arrington & Logan, 2005).

To examine this first research question, three task switching paradigms were used that varied in environmental support. The voluntary task switching paradigm (VTS), which provides no external cues was used to assess switch costs when there is little environmental support available. A great deal of executive control is needed under such circumstances, as the environment offers no information regarding which task should be performed (Arrington & Logan, 2005). Since executive control is strongly recruited for both the WMC and switching task under these circumstances, I hypothesize that WMC and switching will be related using the VTS. This hypothesis is further bolstered by the fact that one of the few previous studies to find a relationship between WMC and switch costs used the VTS (Butler et al., 2011).

In the VTS paradigm, participants choose which task to perform on each trial which also allows for the examination of task choice. How often participants choose a particular task, and switch between tasks can be examined. Participants are instructed to perform each task equally often, and to choose the tasks at random. Task choice is measured to determine how well participants are able to do this. The relationship between WMC and task choice will also be explored in this study. Having to choose which task to perform on each trial, and to so randomly involves creating a random response profile. This is not unlike having to generate a random sequence of numbers on a random number generation task. Previous research has shown that having to randomly generate numbers involves working memory and executive control (Baddeley, Emslie, Kolodny, & Duncan, 1998). Given this, successfully keeping track of task choices to randomly complete the VTS would also be likely to recruit executive control. Thus, I expect task choice to be related to WMC performance. However, the only previous study to examine this has not found a relationship between WMC and task choice (Butler et al., 2011). From a theoretical perspective I expect to find a relationship between these constructs, but it is possible that previous null findings will be replicated.

An un-cued version of the alternating runs (AR) paradigm was used to assess switch costs when an intermediate level of environmental support is available. I expect a moderate negative relationship between switching and WMC using this paradigm as specific instructions are available to guide task performance, but external cues are not. Most of the previous work examining the relationship between WMC and switching has used the alternating runs paradigm (Kane et al., 2003; Kane, Conway, et al., 2007;

Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003) and has consistently failed to find an association. However, they all used the traditional paradigm which includes an external cue to remind participants of which task should be performed on each trial, generally in the form of a grid. This external reminder means that the levels of environmental support are quite similar to what is available in the explicitly cued paradigm (Arrington & Logan, 2005).

To decrease the amount of support available, the AR paradigm in the present study did not have any external cues available. A similar approach has been taken in one previous study, but it is important to note that Kray and Lindenberger (2000) did not use a complex span task to measure WMC. Instead, they used the alpha sorting task, which does not have a dual task component. This task requires participants to remember the first letter of a series of presented words, and to repeat them back by sorting the letters in alphabetical order. When an analysis was done combining a group of younger and older adults, there was a small, negative correlation between WMC and switch costs ($r = -.25$, $p < .01$) (Kray & Lindenberger, 2000). The present experiment will extend these findings by comparing performance on an un-cued AR switching task with performance on a more traditional complex span WMC task to see whether reducing the amount of environmental support by removing external cues has any influence on the relationship. Given this previous research, and the fact that in the present experiment, the amount of environmental support available has been reduced, I hypothesize a negative relationship between WMC and switch costs using the un-cued AR paradigm.

Finally, the explicitly cued paradigm was used to assess switch costs when environmental support is high because an explicit cue is provided on each trial. It has been argued that when environmental support is high, executive control may not be necessary for task performance (Logan & Bundesen, 2003, 2004). Given this, I predict a weak negative relationship between WMC and switching with this paradigm, in line with previous studies that have used some form of external cuing (Hambrick & Altmann, 2015; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003).

Although less executive control is likely needed for performance in the explicitly cued paradigm, findings suggest that executive control processes are not entirely eliminated when direct cues are used (Mayr & Kliegl, 2003; Monsell & Mizon, 2006). So, although a weaker relationship between WMC and switching may be expected using this paradigm, some relationship is still expected as executive control processes are still needed for both tasks. Previous studies using some form of cuing may not have found an association between switching and WMC because they did not examine timing parameters or switch frequency (Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003) or because alternative analysis techniques were not utilized (Draheim et al., 2016).

To summarize, my first research question examines whether the magnitude of the relationship between WMC and switch costs will change depending on the amount of environmental support available. My overall hypothesis is that WMC and switch costs will be related in all of the switching paradigms used. A negative correlation is predicted as those with higher WMC are expected to show smaller switch costs, indicative of better performance on the switching task. Such a hypothesis is difficult to reconcile with much of the previous research which has failed to find a relationship between WMC and switch costs. However, the present experiment implemented a variety of design manipulations not used in previous studies, and used different analysis techniques to examine switching performance. These alterations will be described in more detail below. I also expect the relationship between WMC and switching to vary in magnitude depending on the amount of environmental support available. The relationship between WMC and switch costs should be strongest on the VTS which has little environmental support and thus requires a great deal of top-down control for task performance. The relationship between WMC and switch costs should be weakest on the explicitly cued task switching paradigm when less top-down control is required. Finally, the relationship between WMC and switch costs on the un-cued AR paradigm should fall somewhere in the middle as an intermediate level of environmental support is available.

2.1.2 The role of timing parameters.

Previous studies may have failed to find a relationship between WMC and switching due to the specific timing parameters used in the switching paradigms. My second research question explores whether timing parameters have any impact on the relationship between WMC and task switching. One of the only studies to find an association between these constructs pointed to the important role of timing parameters. A relationship between task switching and WMC was only found at the shortest response-to-stimulus interval (RSI), when time pressure was greatest (Butler et al., 2011). To examine this, timing parameters were varied all three of the switching paradigms used in the present study. The VTS and un-cued AR paradigms included blocks with both short and long RSI's, allowing for an examination of whether time between trials has any impact on the relationship between WMC and switch costs. To examine this in the context of the cued switching paradigm, the response-to-cue interval (RCI) and the cue-to-stimulus interval (CSI) were manipulated. Three different timing conditions were examined (Mayr & Kliegl, 2003). In one condition the RCI was long and the CSI short, allowing for an examination of the role of dissipation of the previous task set (Mayr & Kliegl, 2003; Meiran et al., 2000). In another condition, the CSI was kept long and the RCI short to examine performance when time is available for preparation (Mayr & Kliegl, 2003; Meiran et al., 2000). Finally, in one condition, both the CSI and RCI were kept short leaving no time for dissipation of task set or preparation for the upcoming trial.

Based on previous research, across the three paradigms I expect the relationship between WMC and switch costs to be strongest when time pressure is greatest. This will be at the shortest RSIs in the VTS and un-cued AR paradigm, and in the conditions in which CSI is kept short in the explicitly cued paradigm. Preparation for the upcoming trial will be impossible under these timing conditions. This would be consistent with the findings of the only previous study to explore timing manipulations in the context of examining the relationship between WMC and switching (Butler et al., 2011). It is under these rapid timing conditions, when no time is available for preparation, that the switching task is most challenging. The relationship between WMC and attentional control tasks tends to emerge under the most challenging conditions (Poole & Kane, 2009; Robison, Miller, & Unsworth, 2018). Previous studies may have failed to find an association between switching and WMC because they did not examine different timing parameters in the switching tasks (Hambrick & Altmann, 2015; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003).

2.1.3 The impact of analysis method.

My third research question explores whether previous studies failed to find a relationship between WMC and switch costs because of the analyses they used to explore switch costs.[1] Most of the studies that failed to find a relationship between WMC and task switching assessed performance on the switching task using standard switch cost scoring methods (Gamboz et al., 2009; Hambrick & Altmann, 2015; Kane et al., 2003; Kane, Conway, et al., 2007; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003). This scoring approach involves calculating a difference score between reaction time on switch trials and reaction time on repeat trials, called the switch cost. Switch costs are widely used in cognitive psychology and are the key dependent variable in task switching research (Monsell, 2003; Vandierendonck et al., 2010). Despite their pervasive use, a number of concerns have been raised about the use of difference scores. One issue for task switching, specifically, is that when difference scores are used, reaction time (RT) and accuracy (ACC) are examined independently, and separate analyses are not ideal (Draheim et al., 2016; Hughes et al., 2014). When we examine RT switch costs, we ignore accuracy, and when we calculate ACC switch costs, we ignore RT. Such an approach does not provide information about how the ACC and RT switch costs interact in an individual, thus we may not be getting the full picture by analysing difference scores. We may be overlooking important aspects of task performance.

Another criticism of difference scores is that they tend to have low reliability (Draheim et al., 2016; Edwards, 2001; Hedge et al., 2018; Miller & Ulrich, 2013; Paap & Sawi, 2016). When calculating the reliability of a difference score, one must consider the reliability of the two measures contributing to the difference scores, as well as the relationship between those two measures. If the components are related, reliability tends

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[1] Note that this final research question was not pre-registered, as the article which highlights this as an important consideration was not published until after data collection had already begun (Draheim et al., 2016). However, this research question was added before any data analysis began.

to be relatively low (Edwards, 2001; Miller & Ulrich, 2013). This is often the case in task switching, as switch RT is correlated with repeat RT (e.g., in the present study, the overall correlation between repeat RT and switch RT in the explicitly cued task switching paradigm is $r = .91$, $p < .001$), In such cases, the difference score is generally less reliable than the component scores that went into it.

In individual differences research, another issue is the fact that variance tends to be reduced in difference scores (Hedge et al., 2018). This is problematic when we are using difference scores to conduct correlational research as we are in the present study. Given these potential limitations of difference scores, several alternatives have been proposed which combine RT and ACC into a single score (Hughes et al., 2014). These alternatives show increased reliability and validity when compared to standard switch cost difference scores (Draheim et al., 2016; Hughes et al., 2014).

One study employing these novel methods actually found a significant relationship between WMC and task switching performance in the hypothesized direction (Draheim et al., 2016). However another study failed to find such an association even when combined reaction time and accuracy analyses were used, although a small relationship of ‘marginal significance’ emerged (Pettigrew & Martin, 2016). These studies suggest that the analysis technique used to explore task switching performance may have an important bearing on the relationship between WMC and switching. The present study explored switching performance using the traditional difference score method as well as a method which combining reaction time and accuracy information.

Another novel analysis technique that was employed in the present study involves exploring reaction time variability rather than focussing solely on mean reaction times. None of the previous studies that have examined the relationship between WMC and task switching have used such an approach. Traditionally, the focus in experimental psychology research has been on overall RT, while an examination of individual variability in RT has been largely neglected (Jensen, 1992; MacDonald, Nyberg, & Bäckman, 2006). However, in more recent years, the use of intraindividual variability as an index of cognitive task performance has increased (Duchek et al., 2009; Hultsch, MacDonald, & Dixon, 2002; Kane et al., 2016; MacDonald et al., 2006; McVay & Kane, 2012a; Unsworth, 2015). Intraindividual variability in RT may serve as a meaningful index of executive attentional control abilities. High levels of intraindividual variability may be linked to fluctuations in attentional control. Individuals with good attentional control abilities should perform in a stable manner across the task even in the face of distractions, thus showing low RT variability. In contrast, those with poor attentional control abilities are more likely to be distracted or to have their mind wander from the task and show fluctuations in attention which will likely be reflected in increased variability in their reaction times (Kane et al., 2016; Unsworth, 2015).

There is support for these assertions as high and low WMC participants have shown different levels of intraindividual variability on a sustained attention task. Low WMC participants showed greater RT variability, a greater number of slower responses and a greater range of RTs while high WMC participants showed RTs that were more consistent and moderate (McVay & Kane, 2012a). Intraindividual RT variability on an attentional control factor comprising performance on an antisaccade, arrow flanker, Stroop, and psychomotor vigilance task has also been related to WMC (Unsworth, 2015). Intraindividual variability may be an important piece of the puzzle in examining the relationship between WMC and task switching. Low WMC participants may show more variable RT responding, and thus poorer attentional control during task switching even if this is not necessarily reflected in lower switch costs using traditional difference scores.

Based on previous research, I hypothesize that if standard switch cost scoring methods do not show a significant relationship with WMC, this relationship may be found when scoring methods are used that combine reaction time and accuracy. I also expect to find a relationship between WMC and RT variability. A negative correlation is predicted with low WMC participants showing higher RT variability than those with high WMC.

2.1.4 Exploring switch frequency and congruency.

In addition to the three main research questions highlighted above, there are two other unique aspects of this study that will allow for some exploratory analysis. The first is the frequency of switch trials, and the second is exploring the effect of response congruency. This study is the first to use a 25% frequency of switch trials in the explicit cuing paradigm. Most studies that failed to find a relationship between WMC and switching used 50% switch trials (Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003; Pettigrew & Martin, 2016). Given the nature of the design of their paradigm, Hambrick and Altmann (2015) did not use a 50% switch frequency, but it is unclear from their study exactly what the rate of task switching was. There is reason to believe that using a lower switch frequency may have an impact on the relationship between switching and WMC. The association between WMC and Stroop performance is found only when congruency is 75-80% (Kane & Engle, 2003). It is difficult to maintain the task goal with such congruency levels and larger Stroop effects are seen under such circumstances (Bugg & Crump, 2012). Variations in switch frequency are thought to be analogous to this effect, with switch costs increasing when there is a higher frequency of repeat trials (Bugg & Crump, 2012). As such, I expect to find an association between switching and WMC in a paradigm with 75% repeat trials and only 25% switch trials as it will be more difficult to maintain the task goal under such circumstances. To encourage task-set reconfiguration it is important to keep the probability of a task switch low, and a probability of 25% has been recommended (Monsell & Mizon, 2006). Due to the nature of the paradigm, the un-cued AR paradigm used a 50% switch frequency, and the VTS will encouraged participants to attempt to maintain a 50% switch frequency. If a significant relationship between WMC and switch costs is only found in the cued switching paradigm, it may suggest an important role for switch frequency in this relationship.

The explicitly cued task switching paradigm and the un-cued AR paradigm also allow for an examination of the relationship between WMC and response congruency (See Figure 2 in Chapter 1). With these paradigms, participants respond to both tasks using the same response keys. If a switching task asked people to switch between colour and shape, red and triangle might be mapped to key 1, and blue and rectangle to key 2. Trials can be categorized as congruent, indicating that the response key is the same regardless of the task (e.g., a red triangle) and incongruent, meaning that the correct response key depends on which task is relevant on that trial (e.g., red rectangle). No previous study has examined the relationship between WMC and response congruency in the context of a task switching paradigm. Participants are slower on incongruent trials compared to congruent trials, which is likely due to interference from the irrelevant response (Liefooghe, Wenke, & De Houwer, 2012).

Several theories differ with regard to whether they would predict a relationship between WMC and congruency effects in the context of task switching. The executive attention theory of WMC emphasizes the importance of WMC in overcoming conflict by inhibiting responses to strong, but irrelevant stimuli (Kane, Conway, et al., 2007). The response congruency effect reflects such conflict, so those with the lowest WMC would likely show the highest response congruency effect. However, others have suggested that although working memory is involved in task switching congruency effects, it is not the limited capacity portion of WM that represents the S-R mappings. Instead, congruency effects found in the context of switching paradigms have been proposed to reflect S-R associations and task representations in the activated portion of LTM, which is not limited in capacity (Kessler & Meiran, 2010; Liefooghe et al., 2012; Meiran & Kessler, 2008). Support for this idea comes from studies which have shown that increased WM load does not influence congruency effects in the switching paradigm (Kessler & Meiran, 2010; Kiesel, Wendt, & Peters, 2007). Thus, according to the executive attention theory of WMC (Kane, Conway, et al., 2007), I would expect to find an association between congruency effects and WMC, but according to the activated LTM theories of congruency effects, I would not expect to find such an association (Kessler & Meiran, 2010; Meiran & Kessler, 2008). This study hopes to shed some light on these conflicting hypotheses.

In summary, I expect to find a negative correlation between WMC and task switching with high WMC participant showing the smallest switch costs, indicative of better performance on the switching task. This would be in line with the executive attention theory of WMC (Engle, 2002; Kane, Conway, et al., 2007). The magnitude of the relationship is expected to vary depending on the amount of environmental support available to complete the switching tasks. The strongest association is expected when the least amount of environmental support is present, increasing the amount of top-down control required for successful task performance. It is also expected that the magnitude of the relationship will vary depending in the amount of time available between each trial in the switching task. The highest correlations between WMC and switch costs are expected when time pressure is greatest. Finally, I also expect there to be an impact of the analysis technique used. Although traditional difference score switch cost methods may not elicit the hypothesized relationships; it is expected that these relationships will emerge when more novel methods such as combined RT/ACC analyses, or RT variability analyses are used.

2.2 Method

2.2.1 Pre-registration.

This experiment was pre-registered at the Open Science Framework (OSF) and the pre-registration can be accessed at the following link: https://osf.io/zae3s/?view_only=f7d5565da1df4b0fb80da143e4edf17b. The study was powered to look at the primary analysis of interest, which was the correlation between WMC and task switching. An a priori sample size analysis using G*Power version 3 (Faul, Erdfelder, Lang, & Buchner, 2007) suggested that a sample of 32 would be necessary for this within subject design to detect an effect size of 0.3 with an acceptable error rate (alpha=0.05, beta=0.20). Taking this into account, and attempting to achieve an equivalent number of participants in the counterbalanced conditions, the aim was to collect data from 36 participants for this study. Following a miscalculation in the initial power analysis described above, a subsequent sensitivity analysis revealed that with a sample size of 36, the present study is powered to find an effect size of 0.4 rather than 0.3. This should be noted when interpreting the results. The two previous studies to find a relationship between WMC and task switching found effect sizes ranging from -0.26 to -0.49 (Butler et al., 2011; Draheim et al., 2016).

2.2.2 Participants.

Thirty-nine participants were recruited around the Manawatu campus of Massey University (29 female; age: *M* = 21.00; *SD* = 3.35, maximum age = 30). Three participants were excluded from all analyses for failing to meet the required 85% accuracy on the math portion of the WMC task, leaving 36 participants. Of these, three were excluded from the VTS analyses; two because they had less than 85% accuracy on the task, and one because they switched tasks on fewer than 10% of trials. Two participants were excluded from the cued analyses for failing to achieve 85% accuracy on the cued switching task. All participants reported normal colour vision.

2.2.3 Apparatus and stimuli.

All tasks were presented on a Hewlett-Packard computer using a 22” ViewSonic monitor. Responses were registered with a standard QWERTY keyboard. The operation span task (OSpan) was used to measure WMC and was administered using E-Prime Version 2.0 software (Psychology Software Tools Inc, 2012). The E-Prime program used was downloaded from the Engle Attention and Working Memory Lab, available at http://englelab.gatech.edu/tasks.html (Unsworth et al., 2005). The stimuli used in the OSpan were letters (F, H, J, K, L, N, P, Q, R, S, T, and Y) and a series of mathematical operations.

All of the switching tasks were designed and administered using PsychoPy software (Peirce, 2007). The same stimuli were used across all three switching tasks (see Figure 5) and consisted of bivalent coloured shapes presented on a black background. The stimuli were one of four shapes; a small triangle, large triangle, small rectangle, or large rectangle. The small stimuli were 3 cm tall and 5 cm wide, and the large stimuli were 6 cm in height and 10 cm in width. The size of the stimulus had no bearing on responses. Size was manipulated to increase the number of stimuli, and thus reduce the occurrence of immediate stimulus repetitions. The shapes were presented in one of four colours; red (RGB = 255, 0, 0), blue (RGB = 0, 0, 255), or the grayscale equivalent of red, a light grey (RGB = 76, 76, 76), and the grayscale equivalent of blue, a darker grey (RGB = 29, 29, 29). Each of these colours and shapes were matched, creating 16 unique stimuli. In the explicitly cued switching task, written cues were presented 0.5 cm above each stimulus. All small shapes were presented in the centre of the screen. The large shapes were centred 1.5 cm lower. It was necessary to place the large shapes lower so that the cue would appear in the exact same location on the screen, but still be 0.5 cm above the stimulus on every trial, regardless of stimulus size. Otherwise, participants would have needed to adjust their line of vision based on the size of the stimulus, and this may have impacted the speed of responses.

2.2.4 Materials and procedure.

Each participant completed one WMC task and three switching tasks in a single session which lasted 90 to 105 minutes. The OSpan was completed first, followed by the three switching tasks. The order of the switching tasks was counterbalanced across subjects. Participants were tested individually and received a $20 grocery voucher in exchange for their time. Ethical approval for the research reported in this thesis was obtained from the Massey University Human Ethics Committee: Southern B, Application 15/58.

2.2.4.1 Operation span task.

The OSpan includes both a processing and storage task. An automated version was used for this experiment (Unsworth et al., 2005). The processing portion involved solving arithmetic operations, and the storage component involved remembering a series of letters. Before the experimental trials, three separate practice blocks were completed so that the storage and processing tasks could be practiced both individually and together. The first practice block involved completing the letter span task in isolation. A series of letters were presented on the screen for 800 ms each, and at recall a 3x4 grid of letters appeared, requiring participants to indicate which letters they had seen using the mouse. Recall had to be in the correct order and feedback was provided. In the second practice task, participants performed the math task in isolation. They saw a math operation (i.e. $1*3 + 2 = ?$), and clicked the mouse as soon as they had solved it. A digit was presented on the next screen and participants used the mouse to indicate whether the digit was the correct response to the math operation. Accuracy feedback was provided. In this math practice session, the program timed how long it took each participant to solve the problems so that the experimental session could account for individual differences in mathematical abilities. The mean time to complete the math operations for each individual (+2.5 *SD*) was used as a time limit for completing the math tasks in the experimental trials.

Finally, in the third practice block, participants performed the two tasks together just as they would in the experimental trials. Each trial included both an equation and a letter. First, the math operation was presented, and participants clicked the mouse button to indicate that they had solved it. A digit was then presented and the participant had to judge whether it was the correct or incorrect answer to the math problem. A letter was then shown for 800 ms and this letter had to be remembered. After a series of such trials, the letter grid was displayed and participants selected the letters they recalled in the correct order. Feedback was then presented for 2000 ms indicating how many letters were correctly recalled before the next set of trials began. If participants went over their individual time limits for the math operations, the next trial was presented and the current trial was recorded as an error. This prevented participants from rehearsing letters instead of performing the math task. In the experimental session, the size of each set ranged from 3 to 7 operation-letter pairs, and three sets of each size were presented at random during the experiment for a total of 75 operation-letter trials (See Figure 4 in Chapter 1 for a visual depiction of this task).

The OSpan was selected because it is one of the most widely used complex span tasks and it has been used extensively to classify low and high WMC individuals to test the executive attention theory of WMC (Conway et al., 2005; Kane, Conway, et al., 2007).

2.2.4.2 Explicitly cued task switching paradigm.

On each trial, participants were required to make a judgement about the colour or shape of the stimulus presented. Each trial began with the presentation of an explicit cue instructing the participant which task to perform. When the cue “Colour” was presented, participants performed the colour task, and when the cue “Shape” was presented, they performed the shape task. Task cues were presented for 100 ms or 1000 ms, depending on the block, and remained visible until the response for that trial was given. The cues were printed in white text and presented on a black background. The stimulus was then displayed and remained on the screen until a response was made or 2000 ms had elapsed. If the colour task was cued, participants had to press 1 if the stimulus was coloured, and 2 if it was grey. If the shape task was cued, they pressed 1 if the stimulus was a triangle, and 2 if it was a rectangle. Stimulus-response mappings were counterbalanced across participants. Responses were made with the index and middle finger of the dominant hand. Once a response was provided, the stimulus disappeared, and a blank screen was presented with an RCI of 100 ms or 1000 ms, based on the block. After the RCI, the cue for the next trial appeared. Participants completed 6 experimental blocks of 97 trials. Depending on the block, both RCI and CSI were 100 ms (100-100 ms block), RCI was 1000 ms and CSI was 100 ms (1000-100 ms block), or RCI was 100 ms and CSI was 1000 ms (100-1000 ms block). These three RCI-CSI manipulations cycled through in a block-wise manner. Instructions and stimulus-response reminders were presented before each block.

Within each block, the frequency of switch trials was 25%, and they were unpredictable. This frequency was chosen as it is the optimal way to encourage the use of executive control and task-set reconfiguration (Monsell & Mizon, 2006). A task was repeated 2, 3, or 4 times before a switch in task took place. The task sequence within each block was randomized within subject with the constraints that 25% of trials were switch trials, half of all trials were cued with the word “Colour” and the other half were cued with “Shape”, and half of the trials were congruent and the other half were incongruent in terms of stimulus response mappings. Randomization was also constrained such that there was an equivalent number of congruent and incongruent switch trials and an equivalent number of congruent and incongruent repeat trials. There was also an equivalent number of colour and shape trials within each of those constraints. Each of the 16 stimuli appeared an equal number of times throughout the blocks, and no stimulus was directly repeated.

Before completing the six experimental blocks, participants completed two 16 trial single task practice blocks, and one 32 trial switching practice block. On the first practice block, they performed the colour task on all trials, with an RCI-CSI of 1000-100 ms. On the second block, they completed the shape task on all trials with an RCI-CSI of 100-100 ms, and in the final practice block, participants switched between performing the shape and colour task just as in the experimental blocks with an RCI-CSI of 100-1000 ms. These practice blocks allowed participants to become familiar with the stimulus-response mappings, and to practice in each of the timing situations that would be presented in the experimental blocks. During the practice blocks reminders of the stimulus-response mappings were available at the bottom of the screen. These reminders were removed before the experimental trials began.

2.2.4.3 Un-cued alternating runs (AR) paradigm.

As in the cued switching paradigm, participants had to respond to a stimulus presented on each trial, determining whether the stimulus was coloured or grey if it was a colour trial, and determining whether it was a triangle or rectangle if it was a shape trial. Stimulus-response mappings were held constant from the cued switching paradigm. Again, responses were made with the middle and index finger of the dominant hand using the numbers 1 and 2 on the computer keyboard. Stimuli were presented until a response was made, or until 2000 ms had elapsed. Following stimulus presentation, the response-to-stimulus interval (RSI) was manipulated with either a short (100 ms) or long (1500 ms) duration. The duration of the long RSI in this paradigm is longer than those used in the cued task switching paradigm and the VTS as research has suggested that more time is required for task-set reconfiguration when the un-cued AR paradigm is used (Kray, 2006).

Participants completed 20 experimental blocks of 17 trials. At the beginning of each block, participants were told which task they should begin the block with (Colour (C) or Shape (S)) and then to repeat and switch the task in alternation, creating a task sequence of CCSSCCSS, etc. There were no additional external cues presented to remind participants of which task to perform on each trial. Participants were told that they would need to perform this task sequence over the course of the next 17 trials. Half of the blocks had a short RSI while the other half had a long RSI. Half of each of these blocks began with a colour trial, and the other half began with a shape trial. Half of the stimuli were congruent with regards to response congruency, and half were incongruent. Stimulus presentation was randomized, with the constraint that there could be no exact stimulus repetition. Each of the 16 stimuli appeared an equal number of times throughout the experiment.

Prior to the completion of these experimental blocks, participants completed four practice blocks. The first two practice blocks were 17 trial single task blocks providing participants with practice on each of the tasks individually, with one block including an RSI of 100 ms and the other an RSI of 1500 ms. The third and fourth practice blocks each had 17 trials that allowed participants to practice the switching task that would be performed in the experimental blocks. One of these blocks started with a colour trial, and the other with a shape trial, and one had the long RSI while the other had the short RSI.

2.2.4.4 Voluntary task switching paradigm (VTS).

The VTS used the same stimuli as the other two switching tasks. However, with this paradigm, when a stimulus was presented, participants had to decide on their own whether to perform the colour task or the shape task. Prior to beginning the task, participants were instructed to perform the colour and shape tasks equally often and to do so in a random sequence. The instructions were modified slightly from a previous study (Arrington & Logan, 2004), and asked participants to imagine that they had a coin that said colour on one side and shape on the other and to choose the tasks as if the coin had determined which task should be performed. On each trial, a stimulus was presented and remained on the screen until a response was made or 2000 ms elapsed. Each task was mapped to a different hand, and responses were made with the index and middle fingers. For half of the participants, the left hand performed the colour task and rested over the keys ‘d’ and ‘f’, with participants pressing d if the stimulus was coloured and f if it were grey. The right hand rested over the ‘j’ and ‘k’ keys on the keyboard and performed the shape task, by pressing the ‘j’ key if the stimulus was a triangle, and the ‘k’ key if it was a rectangle. Both hand-to-task mapping and stimulus response mappings were counterbalanced across participants. Following the response to the stimulus, an RSI of 100 ms or 1000 ms was presented before the next stimulus appeared.

Participants completed 6 experimental blocks of 80 trials. Half of the blocks had the long RSI and half had the short RSI. Prior to performing the experimental blocks, participants completed 4 practice blocks of 16 trials each. The first two were single task blocks, to provide participants with practice on performing both the colour and shape tasks individually. One had a short RSI, and the other a long RSI. The third and fourth practice blocks allowed participants to choose which task to perform on each trial just as they would in the experimental blocks. One of the practice VTS blocks had a short RSI, and the other a long RSI. Stimuli were presented randomly on each trial, with the constraint that no stimulus could be directly repeated. Each of the 16 stimuli were presented an equal number of times across the experiment.

The stimuli were identical across the switching tasks, and the structure of the tasks were similar (as seen in Figure 5), although instructions differed substantially. Across all three of the task switching paradigms, participants took self-paced breaks between blocks, and were instructed to complete all of the tasks as quickly and as accurately as possible.

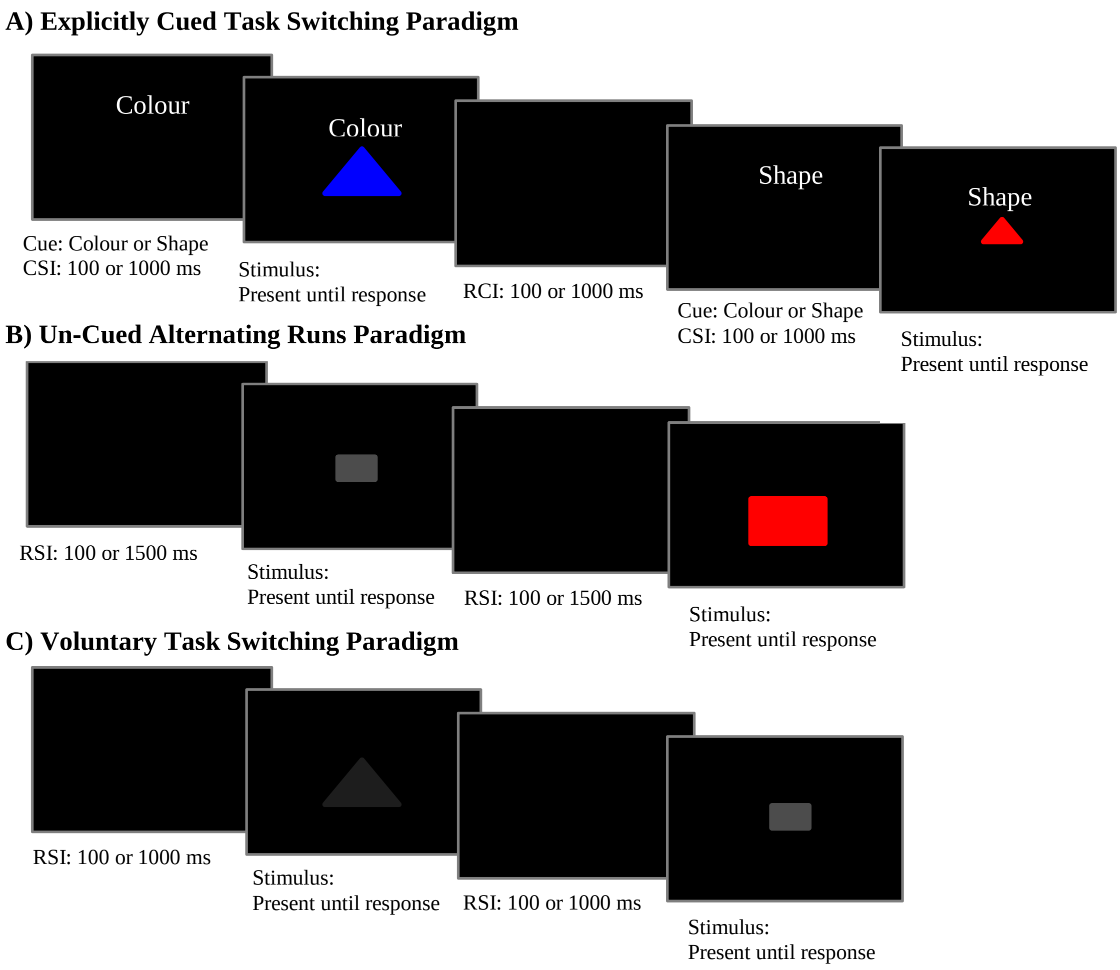


Figure 5. A schematic illustration of the three switching tasks used. For all paradigms, participants performed either the colour task and indicated whether the stimulus was coloured or grey, or the shape task, and indicated whether the stimulus was a triangle or a rectangle. A) For explicitly cued task switching, a cue is presented on each trial instructing the participant of which task to perform. B) In the un-cued alternating runs paradigm, no explicit cues were available. Instead, participants had to remember to switch tasks on every second trial, such that they would perform the shape task twice, followed by the colour task twice, and then they would switch back to the shape task, etc. Participants had to keep track of where they were in the sequence to respond appropriately. C) In the voluntary task switching paradigm, again no external cues were available. Instead, participants decided which task to perform on each trial, attempting to perform the tasks equally often and in a random sequence. Abbreviations: CSI: cue-to-stimulus interval; RCI: response-to-cue interval; RSI: response-to-stimulus interval.

2.2.5 Design and scoring.

This study used a within subject correlational design to examine the relationship between individual differences in WMC and task switching performance. This kind of an individual differences approach can be very useful for testing theories (Meier & Kane, 2017; Underwood, 1975) like the executive attention theory of WMC which is one of the goals of the present thesis. The amount of environmental support available was manipulated by using three switching paradigms with different amounts of cuing information. Timing parameters were also manipulated across the three paradigms. A variety of dependent variables were examined.

2.2.5.1 Working memory capacity.

The main dependent variable from the operation span task was span scores, and two methods were used to calculate these. The absolute span score was calculated by examining the sum of all perfectly remembered sets. In contrast, partial span scores were calculated by summing the total number of items recalled in the correct order, regardless of whether the entire set was remembered correctly. Although the absolute scoring method has been used traditionally in individual differences research using the OSpan (Kane & Engle, 2000, 2003), more recently, the partial scoring method has been recommended as it has somewhat superior psychometric properties (Conway et al., 2005; Redick et al., 2012). Previous research examining the association between task switching and WMC has used both absolute (Pettigrew & Martin, 2016) and partial scoring methods (Butler et al., 2011; Miyake et al., 2000). Given the variability in choice of scoring method in previous WMC research examining task switching, both absolute and partial span scores will be calculated in the present experiment.

2.2.5.2 Task switching.

Difference scores. The main dependent variable for all of the switching paradigms was difference scores. Reaction time switch costs were calculated by subtracting the mean repeat RT from the mean switch RT to create a measure of switch costs. Smaller RT switch costs are indicative of better performance. Accuracy switch costs were calculated by subtracting the percentage of correct responses on switch trials from the percentage of correct responses on repeat trials. Smaller ACC switch costs are indicative of better performance.

Combining RT and ACC: The bin scoring method. Another dependent variable examined was bin scores. The bin scoring method was used to calculate a score on the switching task which combines both ACC and RT. This method involves rank ordering trials based on performance, and binning them into deciles (Draheim et al., 2016; Hughes et al., 2014). This procedure was completed in a series of steps.

1. Cleaning the data – error, post error, and the first trial of each block were removed. Reaction times less than 150 ms were removed. To ensure each participant had the same number of items contributing to their bin score, post-error trials and trials with RTs < 150 ms were replaced with the mean for that trial type.
2. Mean switch and repeat RTs were calculated on a within-subject basis.
3. The participant's mean repeat RT was then subtracted from their RT on each accurate switch trial. This was done on a within-subject basis. This led to an RT difference for every switch trial in every participant.
4. Using the whole sample, all data was grouped together for the binning to take place. All of the RT differences from Step 3 were rank ordered into deciles and a bin value was assigned to each decile. The smallest differences (lowest switch

cost) were assigned to bin 1, the second decile of scores to bin 2, etc. Bin 10 included the 10% of trials with the highest switch costs (poorest performance). This led to the creation of 10 bins, with bin 1 trials showing the lowest cost from switching and bin 10 showing the highest costs.

5. All error trials which had been excluded during the binning process were assigned a bin value of 20. Errors were given a penalty which was double the slowest response on an accurate switch trial. At the end of this step, each switch trial had been assigned a score ranging from 1-10 indicating how costly that trial was compared to the participant's mean RT on repeat trials, or a score of 20, if the response on the switch trial was incorrect.
6. Finally, on a within-subject level, a final bin score was calculated for each participant by summing the scores that were assigned to the switch trials in steps 4 and 5.

A smaller bin score is indicative of better performance. It indicates that on accurate switch trials, the participant showed small RT costs on switch trials relative to their mean repeat RT, and it also indicates that the participant made fewer errors. This process was carried out at each timing manipulation for both the explicitly cued task switching paradigm and the un-cued AR paradigm. This analysis required that each subject had completed the same number of switch trials. Given this, the bin scoring method was not completed for the voluntary task switching paradigm as the proportion of switch trials present for each participant was extremely variable.

Intraindividual RT variability (CoV). To examine intraindividual variability in the context of the switching tasks, the Coefficient of Variation ((CoV) = *SD/M*) in response times was calculated for each participant. The more conservative approach to this calculation was taken by measuring CoV from repeat trials only (Kane et al., 2016).

This approach was chosen to avoid confounding the experimental effect of interest (switch costs) with the RT variability I was seeking to measure (Kane et al., 2016; Meier et al., 2018). However, the pattern of results was similar when the CoV was calculated using all trial types, which is another approach that has been used (Unsworth, 2015).

2.3 Results

The first trial from each block, error, post-error, and trials with RTs less than 150 ms were excluded from all reaction time analyses. The first trial from each block and the RTs less than 150 ms were excluded from all accuracy analyses. Eliminating error and post-error trials led to the exclusion of 12% of trials from the explicitly cued switching analysis, 9% of trials from the alternating runs analyses and 12% of trials from the VTS analyses. Eliminating all trials with an RT less than 150 ms led to the exclusion of 0.01% of trials from each of the switching paradigms. For the alternating runs paradigm, all blocks with three of more errors were excluded as it was likely that participants lost track of the task sequence in those blocks. This led to the exclusion of 6% of the blocks.

For the cued and alternating runs paradigms, switch and repeat trial types were clearly defined before the experiment. For the VTS, the trials were sorted into colour and shape trials based on the hand used to perform the task, and were than sorted into switch and repeat based on the hand used to perform trial n and trial n-1.

2.3.1 Task performance.

Before addressing the three specific research questions, a series of repeated measures ANOVA's were used to explore task performance across the three switching tasks. If Sphericity was violated and the Greenhouse-Geisser Epsilon value was > 0.75, the Huynh-Feldt correction was applied. If the Greenhouse-Geisser Epsilon was < 0.75, the Greenhouse-Geisser correction was applied as recommended (Howell, 2010).

2.3.1.1 Explicitly cued task switching paradigm.

A 2 (trial type; switch versus repeat) x 3 (timing; RSI-CSI: 100-100 ms versus 100-1000 ms versus 1000-100 ms) repeated-measures ANOVA revealed a significant main effect of trial type, showing a significant switch cost for both RT, F (1, 33) = 199.34, $p < .001$, and ACC, F (1, 33) = 47.31, $p < .001$. Participants were slower and more error prone on switch trials ($M \pm SE$; RT: 869 ms ± 22; ACC: 89.5% ± 1.0) relative to repeat trials (RT: 743 ms ± 18; ACC: 94.7% ± 0.5). There was also a main effect of timing for both RT, F (1.77, 58.41) = 207.96, $p < .001$, and ACC, F (1.77, 58.44) = 25.78, $p < .001$. Participants were faster and more accurate on the RCI-CSI 100-1000 ms blocks (RT: 667 ms ± 20; ACC: 94.7% ± 0.6) when they had time available to prepare for the upcoming stimulus, as compared to blocks in which no time was available for preparation (RCI-CSI 100-100 ms: RT: 882 ms ± 21, $p < 0.001$; ACC: 90.3% ± 1.0, $p < .001$; RCI-CSI 1000-100 ms: RT: 869 ms ± 21, $p < .001$; ACC: 91.3% ± 0.7, $p < .001$). There were no significant differences between the RCI-CSI 100-100 ms or 1000-100 ms blocks for either RT ($p = .73$) or ACC ($p = .58$).

There was also a significant trial type by timing interaction for both RT, F (2, 66) = 79.95, $p < .001$, and ACC, F (2, 66) = 11.04, $p < .001$. Although switch costs were significant across all three timing manipulations, the magnitude of the switch costs differed. Both RT and ACC switch costs were reduced when participants had time available for preparation (RCI-CSI 100-1000 ms) when compared to the blocks in which no time was available for preparation (RCI-CSI 100-100 ms and 1000-100 ms). Switch costs were similar across the two timing manipulations that did not allow for advanced preparation. Figure 6 shows the mean RT and ACC for task switch and task repeat trials across the three timing manipulations.

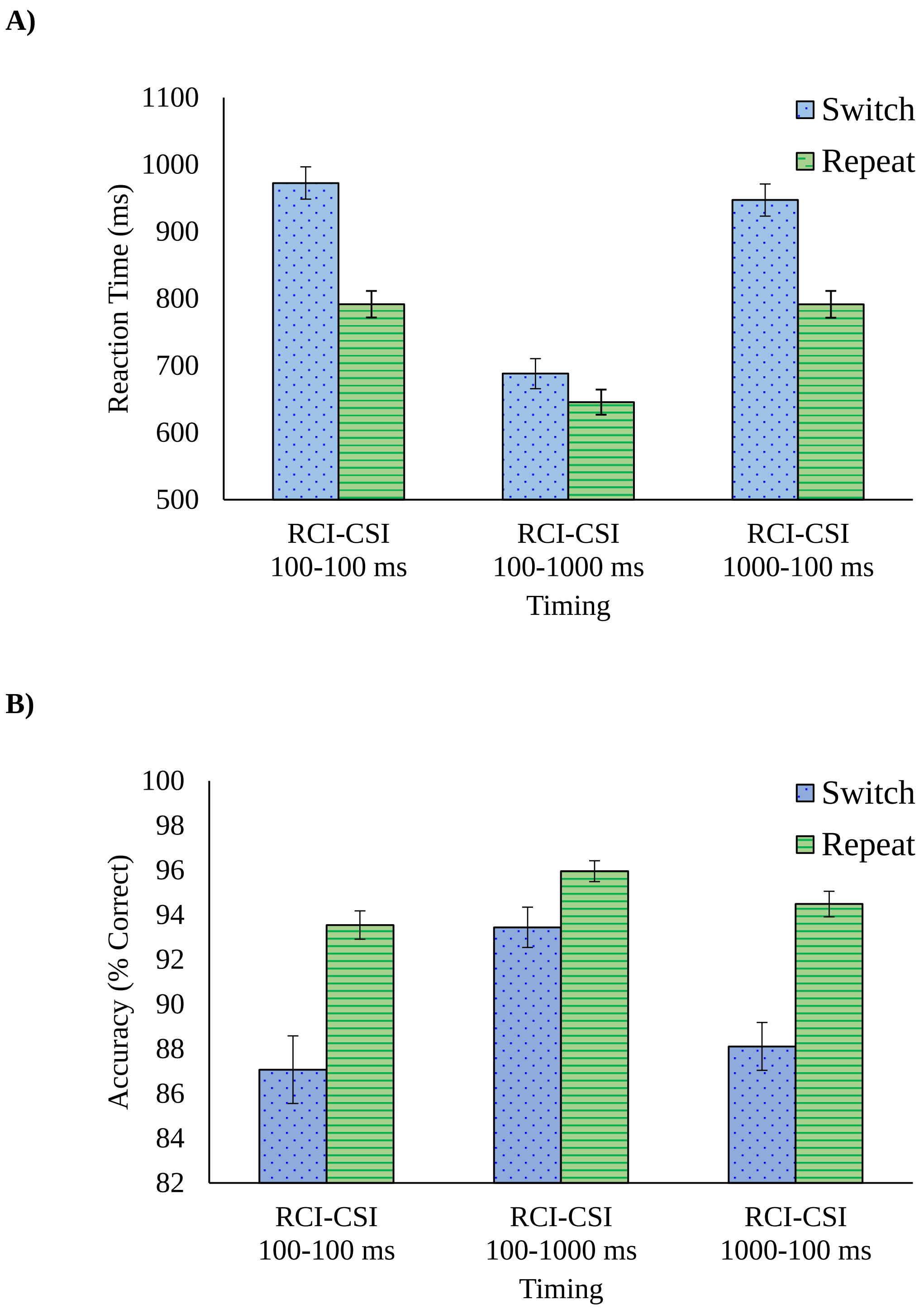


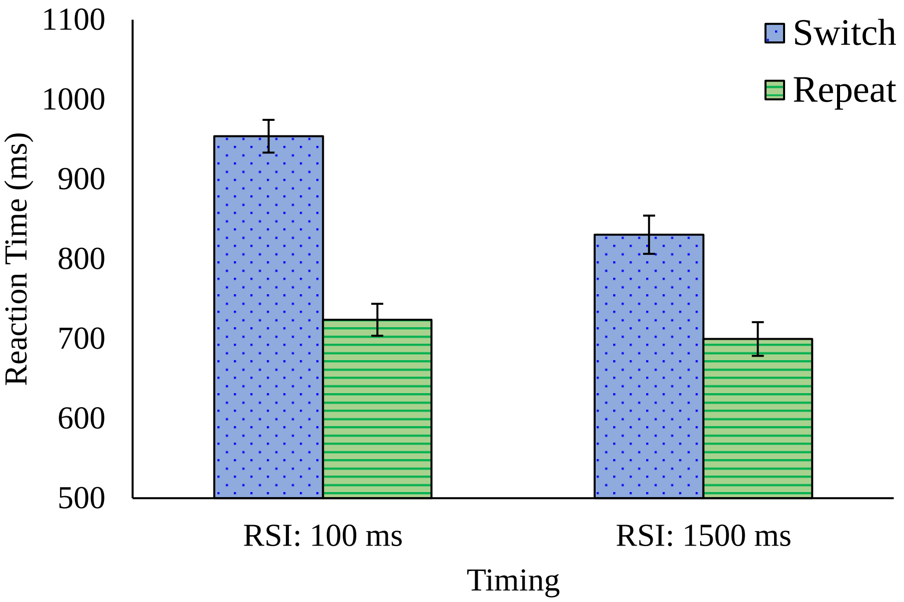
Figure 6. Mean reaction time (A) and accuracy rates (B) for task switch and repeat trials in the cued task switching paradigm.Results are shown across the three timing manipulations used in this paradigm. RCI: Response-to-cue interval; CSI: cue-to-stimulus interval. Error bars indicate standard error of the mean.

2.3.1.2 Un-cued alternating runs paradigm.

A 2 (trial type; switch versus repeat) x 2 (timing; RSI: 100 ms versus 1500 ms) repeated-measures ANOVA revealed a main effect of trial type, which showed a significant switch cost for both RT, *F* (1, 35) = 352.16, *p* < .001, and ACC, *F* (1, 35) = 61.46, *p* < .001. Participants were slower and more error prone on switch trials (*M* ± *SE*; RT: 892 ms ± 20; ACC = 93.3% ± 0.6) as compared to repeat trials (RT: 712 ms ± 19; ACC: 96.9% ± 0.4). There was not a main effect of timing for ACC, however there was for RT, *F* (1, 35) = 18.05, *p* < .001. Participants were significantly faster when they had time to prepare for the upcoming stimulus (RSI: 1500 ms; RT = 765 ms ± 22) compared to when no time was available for advanced preparation (RSI: 100 ms: RT = 839 ms ± 19, *p* < .001).

For RT, there was also a significant interaction between trial type and timing, *F* (1, 35) = 43.94, *p* < .001. Participants benefitted from having time available to prepare for the upcoming stimulus. While switch costs were significant in both timing manipulations, they were smaller in the 1500 ms condition as compared to the 100 ms condition. Figure 7 shows the mean RT and ACC for task switch and task repeat trials across the two timing manipulations.

A)



B)

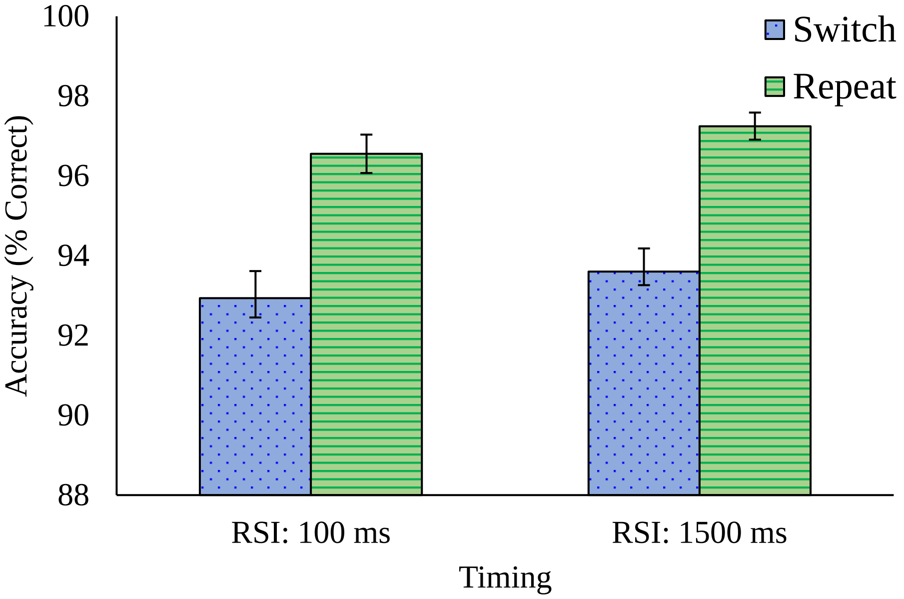


Figure 7. Mean reaction time (A) and accuracy rates (B) for task switch and repeat trials in the un-cued alternating runs task switching paradigm. Results are shown across the two timing manipulations used in this paradigm. RSI: response-to-stimulus interval. Error bars indicate standard error of the mean.

2.3.1.3 ***Voluntary task switching paradigm.***

A 2 (trial type; switch versus repeat) x 2 (timing; RSI 100 ms versus 1000 ms) repeated-measures ANOVA revealed a significant main effect of trial type, showing a significant switch cost for both RT, *F* (1, 32) = 150.23, *p* < .001 and ACC, *F* (1, 32) = 4.44, *p* = .04. Participants were slower and more error prone on switch trials (*M* ± *SE*; RT: 863 ms ± 21; ACC: 94.8% ± 0.6) as compared to repeat trials (RT: 717 ms ± 21; ACC: 95.7% ± 0.5). For RT, there was also a main effect of timing (*F* (1, 32) = 7.41, *p* = .01), with participants performing significantly faster when they had time to prepare in the 1000 ms condition (RT: 770 ms ± 22) compared to when they did not have time to prepare in the 100 ms condition (RT: 809 ms ± 21). There was also a significant interaction between trial type and timing, *F* (1, 32) = 60.36, *p* < .001. Once again, participants benefitted from having time to prepare. Switch costs were smaller in the 1000 ms condition as compared to the 100 ms condition (See Figure 8). The interaction between trial type and timing was not significant for ACC. Figure 8 shows the mean RT and ACC for task switch and task repeat trials across the two timing manipulations in the voluntary task switching paradigm.

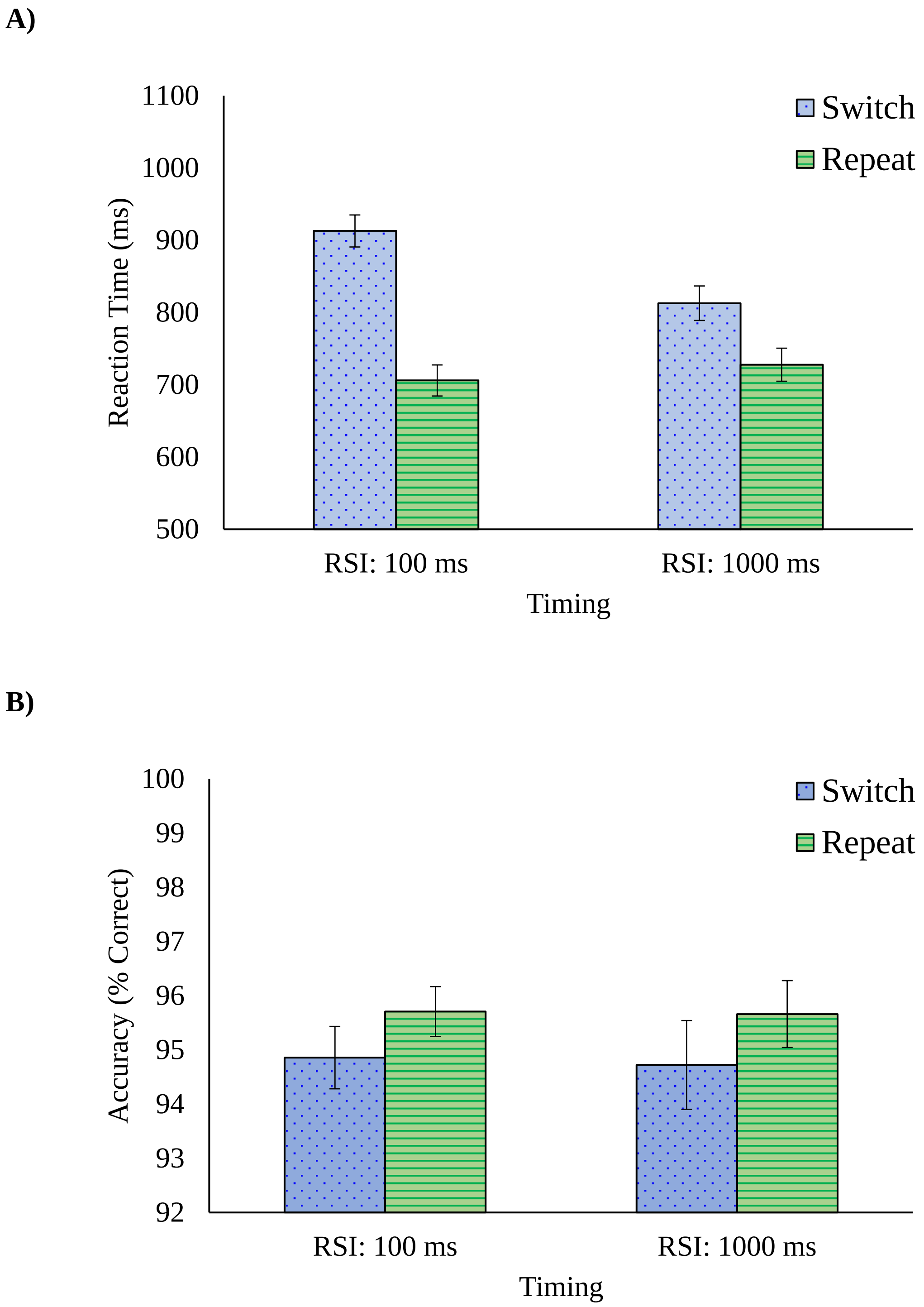


Figure 8. Mean reaction time (A) and accuracy rates (B) for task switch and repeat trials in the voluntary task switching paradigm. Results are shown across the two timing manipulations used in this paradigm. RSI: response-to-stimulus interval. Error bars indicate standard error of the mean.

2.3.1.4 Working memory capacity.

Absolute span scores ranged from 3 to 69 (*M* = 41.81, *SD* = 16.10) and scores were normally distributed, *K-S* (36) = 0.11, *p* = .20. Partial span scores ranged from 22 to 74 (*M* = 59.19, *SD* = 10.91), however the partial span scores violated the assumption of normality *K-S* (36) = 0.15, *p* = .04. Given the greater variability in the absolute span scores, which will allow for better discrimination among high and low WMC participants, and the fact that partial span scores were not normally distributed, all results presented will be for the absolute span scores. It should be noted that absolute and partial span scores were significantly correlated (*r* (34) = 0.89, *p* < .001) and the pattern of results was similar when analyses were completed using partial span scores.

2.3.2 The association between working memory capacity and task switching.

2.3.2.1 Traditional switch cost analyses.

The assessment of task performance clearly shows that significant switch costs were found in all three of the task switching paradigms. It also showed that these switch costs were impacted by timing parameters. To examine research questions 1 and 2, a series of correlational analyses were conducted to examine the relationship between switch costs and WMC. This was done across the three switching paradigms to address research question 1 about whether the amount of environmental support would influence the magnitude of the relationship between these constructs. It was hypothesized that we would find a significant negative correlation in all three switching paradigms, but we expected this correlation to be strongest in the VTS, and weakest when the explicitly cued switching paradigm was used. These correlations were run separately for each of the timing manipulations used to address research question two which aimed to examine the role of timing on the relationship between WMC and task switching. It was hypothesized that the relationship between WMC and switching would be strongest when time pressure was greatest.

As seen in Table 1, RT switch cost difference scores were not related to WMC in any of the task switching paradigms (See Figures 9 and 10 for scatterplots of these relationships). This finding held for overall RT switch costs and switch costs in each of the timing manipulations across the paradigms. Similarly, ACC switch costs were largely unrelated to WMC across the three task switching paradigms (See Figure A-1 and Figure A-2 for scatterplots of the relationship between WMC and ACC). A relationship between ACC switch costs and WMC was found in the explicitly cued task switching paradigm in the 1000-100 ms condition. This is interesting, as this is the timing condition in which no time is available for preparation, so a negative relationship between WMC and switch costs would be predicted. Some caution should be noted as the results in Table 1 have not been corrected for multiple comparisons. RT switch costs demonstrated internal consistency reliabilities close to the recommended acceptable level of .70, across all three task switching paradigms (Nunnally, 1978). However, ACC switch costs were not very reliable for the alternating runs and voluntary task switching paradigms. Specifically for the VTS, this is not surprising given the complexities of scoring accuracy information in this paradigm. It is not possible to determine whether participants have used the incorrect hand in responding, or the incorrect finger.

2.3.2.2 Bin scores.

To address research question three, the analyses just described were repeated using more novel analysis techniques such as bin scores and CoV. It was hypothesized that if traditional switch costs failed to find a relationship between WMC and task switching, a relationship may be found when new analysis techniques were implemented. A negative correlation between WMC and bin scores was expected because smaller bin scores are indicative of better performance. The results of these correlations can be found in Table 1. When RT and ACC were combined, and bin scores were examined, internal consistency reliability increased above acceptable levels. However, despite this increase in reliability, WMC showed no relationship to task switching. WMC was not related to bin scores in either of the task switching paradigms examined, or under any of the timing manipulations (See Figures 11 and 12 for scatterplots of these relationships). These initial analyses suggest that there is no relationship between switch costs and WMC when performance on the switching paradigm is assessed using traditional RT switch cost methods, or more novel methods such as bin scoring. A single significant correlation emerged between ACC switch costs and WMC in one timing manipulation of the cued switching paradigm. Given that this did not emerge in any of the other paradigms, or for ACC switch costs in the other timing manipulation that also did not allow for preparation, and given the lower level of reliability for ACC switch costs, one should not over-interpret this single result.

Table 1

Descriptive Statistics, Reliabilities, and Correlations with WMC for RT and ACC Switch Costs and Bin Scores across the Three Task Switching Paradigms

Measure	*M*	*SD*	Reliability	WMC *r*	*p*
Switch Cost RT (Switch – Repeat (ms))					
Cue Overall	124	52	.69	-.14	.44
Cue 100-100 ms	181	66		-.12	.48
Cue 100-1000 ms	43	56		-.15	.41
Cue 1000-100 ms	156	72		-.09	.62
AR Overall	178	57	.71	-.09	.60
AR 100 ms	230	77		-.18	.29
AR 1500 ms	131	70		.05	.76
VTS Overall	140	67	.75	-.21	.24
VTS 100 ms	207	85		-.08	.65
VTS 1000 ms	85	78		-.32	.07
Switch Cost ACC (Repeat – Switch (%))					
Cue Overall	5.1	4.3	.66	-.24	.18
Cue 100-100 ms	6.5	6.6		-.03	.88
Cue 100-1000 ms	2.5	3.8		-.25	.16
Cue 1000-100 ms	6.4	5.5		-.35*	.04
AR Overall	3.6	2.8	.28	-.33	.05
AR 100 ms	3.6	3.4		-.27	.11
AR 1500 ms	3.6	3.4		-.25	.15
VTS Overall	0.9	2.5	.16	-.15	.39
VTS 100 ms	0.9	3.5		-.25	.16
VTS 1000 ms	0.9	3.1		.02	.90
Bin Scores					
Cue Overall	1010	139	.82	-.18	.31
Cue 100-100 ms	354	61		-.09	.60
Cue 100-1000 ms	310	53		-.22	.20
Cue 1000-100 ms	347	53		-.23	.19
AR Overall	6.5	0.9	.81	-.21	.23
AR 100 ms	6.5	1.3		-.20	.25
AR 1500 ms	6.4	1.0		-.12	.51

Note. Cronbach's alpha reliabilities were calculated for the explicitly cued task switching paradigm, and the VTS across all 6 blocks of the experiment. For the AR paradigm, many participants were missing block-level data, so, the reliability analysis was run using switch costs from each quarter of the experiment. All tests are 2-tailed. $*p < .05$. For switch cost RT, the AR 1500 ms and overall variable violated normality, so Spearman's rho was calculated; 1500 ms: ρ (34) = .08, *p* = .65; overall: ρ (34) = -.16, *p* = .36. For switch cost ACC, the Cue 100-100 ms variable also violated normality; ρ (32) = -.12, *p* = .50. WMC: working memory capacity; Cue: Explicitly cued task switching paradigm; AR: alternating runs; VTS: voluntary task switching; RT: reaction time; ACC: accuracy.

2.3.2.3 ***The coefficient of variation (CoV).***

Mirroring the results presented above, there was little relationship between WMC and the CoV in any of the task switching paradigms. For the explicitly cued task switching paradigm, WMC was not related to CoV overall, *r* (32) = .29, *p* = .09, or in the 100-1000 ms, *r* (32) = .20, *p* = .25 or 1000-100 ms, *r* (32) = .15, *p* = .39 timing conditions. However, in the 100-100 ms timing condition, there was a significant positive relationship between WMC and CoV, *r* (32) = .36, *p* = .04 suggesting that those with lower WMC actually showed less intraindividual variability. This finding is in the opposite direction to what we would have expected. In the un-cued alternating runs paradigm, WMC was not related to CoV overall, *r* (34) = -.02, *p* = .92, or in either of the timing conditions (RSI 100 ms: *r* (34) = .02, *p* = .93; RSI 1500 ms: *r* (34) = .10, *p* = .56). Similarly, in the VTS, WMC was not related to CoV overall, *r* (31) = -.04, *p* = .81, or in either of the timing conditions (RSI 100 ms: *r* (31) = -.03, *p* = .89; RSI 1000 ms: *r* (31) = -.12, *p* = .51). Even with this novel index of executive attention, the CoV, we were unable to find any relationship with WMC (See Figure A-3 and Figure A-4 for scatterplots of the relationship between WMC and CoV).

2.3.2.4 ***Congruency effects.***

Another aspect of the switching tasks that were examined was response congruency. This was examined for both the explicitly cued switching paradigm and the un-cued alternating runs paradigm. Congruency was not examined on the VTS as there were no overlapping response keys. On the explicitly cued task switching paradigm, there was evidence of congruency costs. Participants were significantly faster on congruent trials (RT: *M* = 748 ms, *SD* = 111) as compared to incongruent trials (RT: *M* = 797 ms, *SD* = 111), *t* (33) = -8.11, *p* < .001. Similarly, participants were also more accurate on congruent (ACC: *M* = 96.9%, *SD* = 2.3) as compared to incongruent trials (ACC: *M* = 90.0%, *SD* = 5.2), *t* (33) = 9.10, *p* < .001. The same pattern emerged on the un-cued alternating runs paradigm. Participants were significantly faster on congruent trials (RT: *M* = 785 ms, *SD* = 112) compared to incongruent trials (RT: *M* = 816 ms, *SD* = 114), *t* (35) = -6.67, *p* < .001. They were also more accurate on congruent (ACC: *M* = 96.7%, *SD* = 2.1) compared to incongruent trials (ACC: *M* = 93.4%, *SD* = 3.5), *t* (35) = 6.06, *p* < .001.

To examine whether there is a relationship between WMC and congruency costs in either of these paradigms, correlations were run for both RT and ACC. Given the novel nature of this particular research question, it was unclear whether a relationship would emerge. RT congruency costs were calculated as incongruent RT minus congruent RT, as in previous studies (Monsell & Mizon, 2006). ACC congruency costs were calculated as congruent ACC minus incongruent ACC. For the explicitly cued task switching paradigm, WMC was not related to RT congruency costs (*M* = 49 ms; *SD* = 35), *r* (32) =.02, *p* = .90, or ACC congruency costs (*M* = 7%; *SD* = 4), *r* (32) = .14, *p* = .44. Similarly, in the un-cued alternating runs paradigm, WMC was not related to RT congruency costs (*M* = 32 ms, *SD* = 29), *r* (34) = -.09, *p* = .62 nor ACC congruency costs (*M* = 4%, *SD* = 4), *r* (34) = -.05, *p* = .78. Overall, there was no relationship between WMC and congruency effects. See Figure A-5 in Appendix A for scatterplots of these relationships.

2.3.2.5 Task choice.

In addition to exploring switch costs, the VTS allowed for the exploration of task choice. This involved calculating the probability with which the colour and shape tasks were chosen, and the probability of switching tasks versus repeating the same task.

In the VTS, there was no bias regarding which task was chosen with participants performing the colour task and the shape task equally often. The mean proportion of trials on which the shape task was performed was 0.49991, which was not significantly different from 0.50, t (32) = -0.24, p = .98. However, as expected, participants showed a strong bias towards repeating with the mean switch probability (0.35) being significantly less than 0.5, t (32) = -6.66, p < .001). The probability of switching was not correlated to WMC overall, r (31) = .06, p = .73, or in the 100 ms, r = .04, p = .81, or 1000 ms, r (31) = .09, p = .61 timing conditions.

2.3.3 Exploratory analyses.

In addition to completing the planned analyses which addressed each of the research questions, some exploratory analyses were also conducted. Although the correlational analyses completed in the entire sample did not reveal a consistent pattern of any kind of relationship between WMC and task switching, I was interested in whether a different pattern of results might emerge in high WMC versus low WMC participants. To examine this, a median split analysis was conducted. The median absolute span score was 42, so participants were split into a low WMC group (WMC score ≤ 42; cued task switching: N = 17; AR: N = 19; VTS: N = 16) and a high WMC group (WMC score > 42, cued task switching: N = 17; AR: N = 17; VTS: N = 13). Descriptive statistics comparing the switch costs between high and low WMC participants along with the correlation between switch costs and WMC can be found in Table 2.

Table 2

Task Switching Descriptive Statistics and Correlations with WMC Across the Three Switching Paradigms for Low (WMC≤42) and High (WMC>42) WMC

Measure	*M*	*SD*	WMC *r*	*p*
Switch Cost RT (Switch – Repeat (ms))				
RT Cued Switch Costs				
Low WMC	119	52	-.66*	.004
High WMC	129	54	-.08	.77
RT Cued Switch Cost 100-100				
Low WMC	178	64	-.52*	.03
High WMC	184	70	-.004	.99
RT Cued Switch Cost 100-1000				
Low WMC	34	56	-.60*	.01
High WMC	51	57	-.42	.09
RT Cued Switch Cost 1000-100				
Low WMC	153	80	-.44	.07
High WMC	158	66	.20	.44
RT AR Switch Costs				
Low WMC	171	49	-.52*	.02
High WMC	185	65	-.26	.32
RT AR Switch Cost 100				
Low WMC	228	73	-.48*	.04
High WMC	232	83	-.30	.24
RT AR Switch Cost 1500				
Low WMC	118	61	-.28	.24
High WMC	145	77	-.15	.58
RT VTS Switch Costs				
Low WMC	142	59	-.51*	.03
High WMC	138	78	-.19	.49
RT VTS Switch Cost 100				
Low WMC	196	72	-.47*	.049
High WMC	220	101	-.34	.21
RT VTS Switch Cost 1000				
Low WMC	101	66	-.39	.12
High WMC	66	89	-.10	.71
Switch Cost ACC (Repeat – Switch (%))				
ACC Cued Switch Costs				
Low WMC	5.6	3.4	-.44	.08
High WMC	4.6	5.2	-.13	.63
ACC Cued Switch Cost 100-100				
Low WMC	5.5	4.7	-.54*	.03
High WMC	7.5	8.1	-.14	.60
ACC Cued Switch Cost 100-1000				
Low WMC	3.0	2.8	-.37	.14
High WMC	2.0	4.6	-.21	.42

Measures	*M*	*SD*	WMC *r*	*p*
ACC Cued Switch Cost 1000-100				
Low WMC	8.3	5.2	-.17	.51
High WMC	4.4	5.2	.02	.95
ACC AR Switch Costs				
Low WMC	3.6	3.2	-.66*	.002
High WMC	3.7	2.3	-.53*	.03
ACC AR Switch Cost 100				
Low WMC	3.6	3.3	-.52*	.02
High WMC	3.7	3.6	-.58*	.01
ACC AR Switch Cost 1500				
Low WMC	3.6	4.1	-.63*	.004
High WMC	3.7	2.6	-.14	.60
ACC VTS Switch Costs				
Low WMC	1.1	2.9	-.24	.33
High WMC	0.7	2.0	.12	.68
ACC VTS Switch Cost 100				
Low WMC	1.7	3.6	-.25	.32
High WMC	-0.2	3.2	.47	.08
ACC VTS Switch Cost 1000				
Low WMC	0.7	3.5	-.09	.71
High WMC	1.2	2.7	-.10	.72
Bin Scores				
Cued Bin Scores				
Low WMC	996	134	-.66*	.004
High WMC	1025	146	-.32	.21
Cued Bin Score 100-100				
Low WMC	341	55	-.70*	.002
High WMC	367	66	-.35	.17
Cued Bin Score 100-1000				
Low WMC	309	53	-.51*	.04
High WMC	311	55	-.38	.13
Cued Bin Scores 1000-100				
Low WMC	349	60	-.49*	.047
High WMC	344	45	-.07	.80
AR Bin Scores				
Low WMC	6.4	0.9	-.59*	.007
High WMC	6.6	1.0	-.50*	.04
AR Bin Score 100				
Low WMC	6.5	1.2	-.47*	.04
High WMC	6.6	1.4	-.50*	.04
AR Bin Score 1500				
Low WMC	6.3	1.1	-.52*	.02
High WMC	6.6	0.8	-0.32	.21

Note. * $p < .05$. WMC: working memory capacity; AR: alternating runs; VTS: voluntary task switching; RT: reaction time; ACC: accuracy.

2.3.3.1 Exploratory traditional switch cost analyses.

An interesting pattern of results emerged when the relationship between WMC and switch costs were examined separately for those with high versus low WMC. For RT switch costs, when the relationship in the low WMC subgroup was examined, the expected significant negative correlation between WMC and switch costs was found across all three task switching paradigms. In the explicitly cued switching paradigm, in low WMC participants, a relationship between switch costs and WMC was found for overall switch costs, and this relationship was also significant in the 100-100 ms condition and 100-1000 ms condition. Similarly, for the un-cued alternating runs paradigm, a relationship was found for overall switch costs and for switch costs in the 100 ms condition. This same pattern appeared in the VTS paradigm, with WMC showing a relationship with overall switch costs and switch costs in the 100 ms condition.

Surprisingly, a completely different pattern of results was seen for high WMC participants. No relationship between WMC and switch costs was found in any of the switching paradigms across any of the timing manipulations. Although low WMC participants fairly consistently showed a significant relationship between WMC and switch costs, this was not seen for high WMC participants. Scatterplots displaying the relationships between WMC and RT switch costs on the explicitly cued task switching paradigm can be found in Figure 9, and on the AR and VTS paradigms in Figure 10.

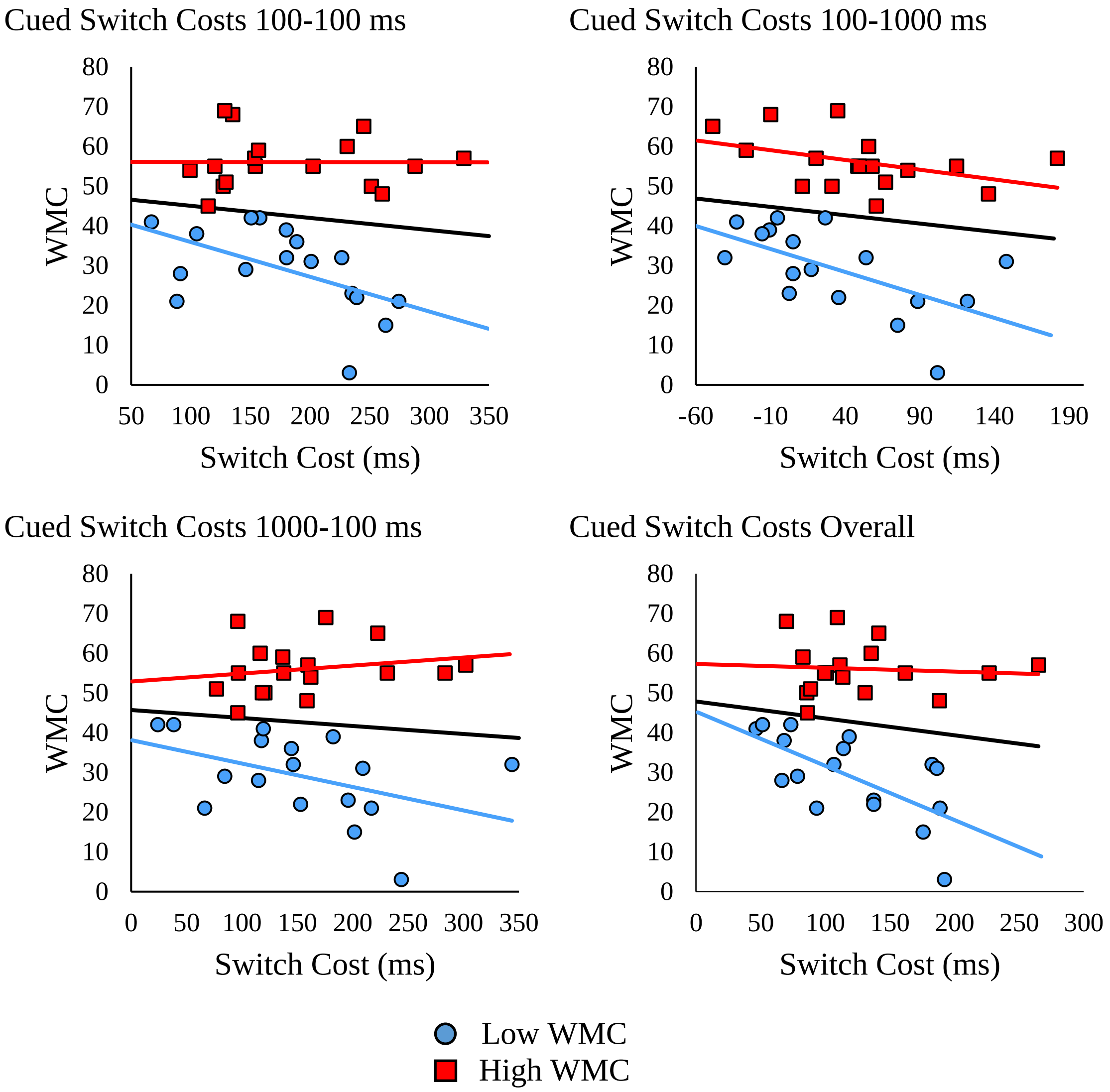


Figure 9. Scatterplots demonstrating the relationship between working memory capacity (WMC) and reaction time switch costs on the explicitly cued switching paradigm. The relationship is shown for low and high WMC participants overall and across the three timing manipulations used in this switching paradigm. The centre line indicates the regression line for the full sample.

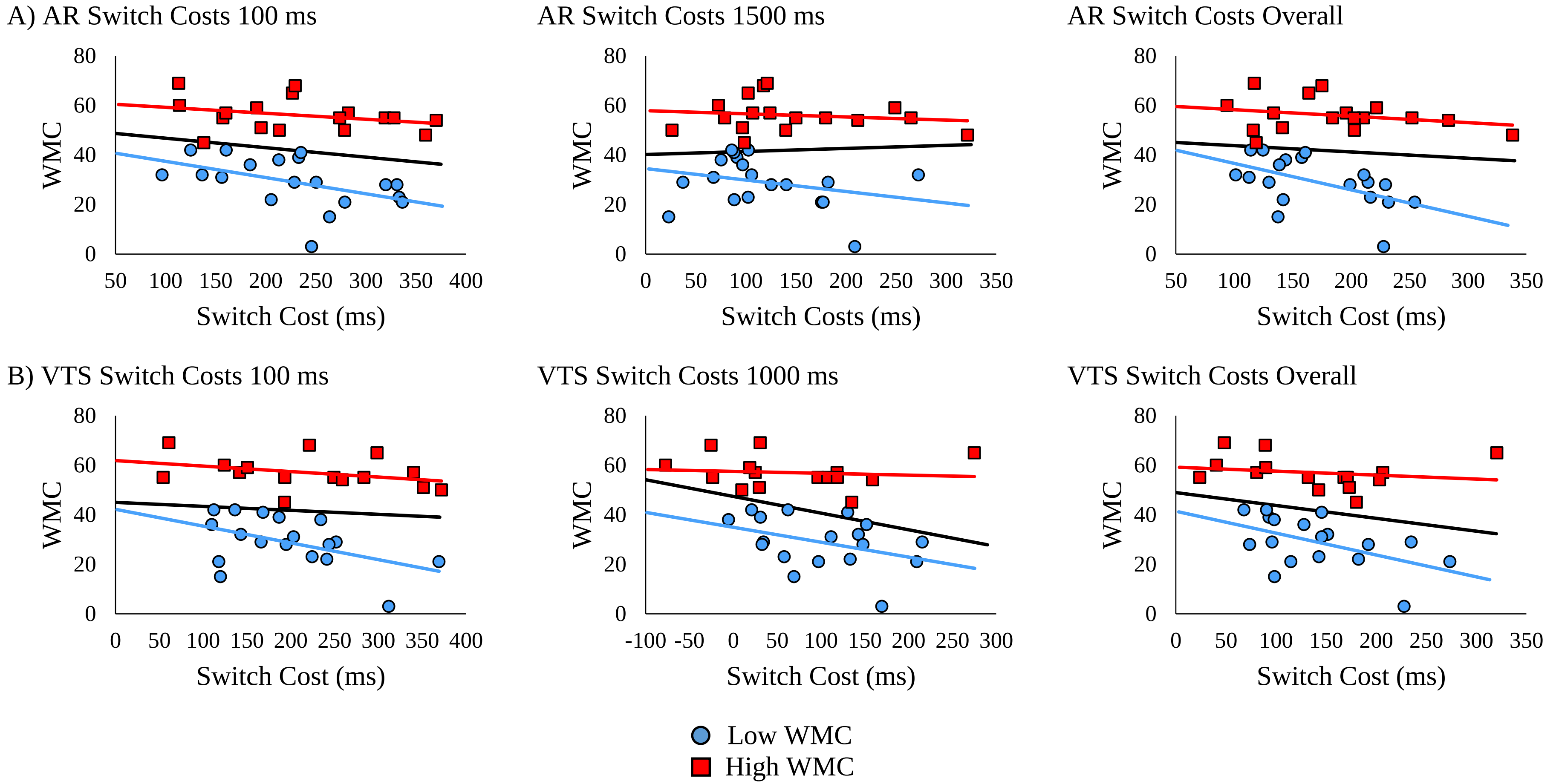


Figure 10. Scatterplots demonstrating the relationship between working memory capacity (WMC) and reaction time switch cost on the A) alternating runs (AR) and B) voluntary task switching (VTS) paradigms. The relationship is shown for low and high WMC participants overall and across the two timing manipulations used in these switching paradigms. The centre line indicates the regression line for the full sample.

The findings for ACC switch costs are a little less clear cut. A relationship between WMC and switch costs was found for the explicitly cued switching paradigm on the 100-100 ms condition for low WMC participants, however no relationship was found in high WMC participants. In the alternating runs paradigm, a relationship between WMC and switch costs was found for both high and low WMC participants overall and in the 100 ms condition, but only for low WMC participants in the 1500 ms condition, and no relationship was found between ACC switch costs and WMC in the VTS paradigm (See Figure A-1 and Figure A-2 for scatterplots of these relationships).

2.3.3.2 Exploratory bin score analyses.

Looking at the results from the bin scores, once again, the expected relationship between WMC and switch costs seems to emerge more in low WMC participants than in the high WMC subgroup. For low WMC participants in the explicitly cued task switching paradigm, the relationship between WMC and bin scores is stronger than in the RT switch costs analyses. This relationship was significant overall and across all three timing conditions in the experiment. This was only the case for low WMC participants, with high WMC participants showing no relationship between WMC and task switch bin scores under any of the timing conditions. In the alternating runs paradigm, overall bin scores were related to WMC overall and in the 100 ms condition for both low and high WMC, however only low WMC participants showed a relationship in the 1500 ms condition. Scatterplots displaying the relationship between WMC and bin scores in the explicitly cued switching paradigm can be found in Figure 11. Figure 12 displays the relationship between WMC and bin scores in the AR paradigm.

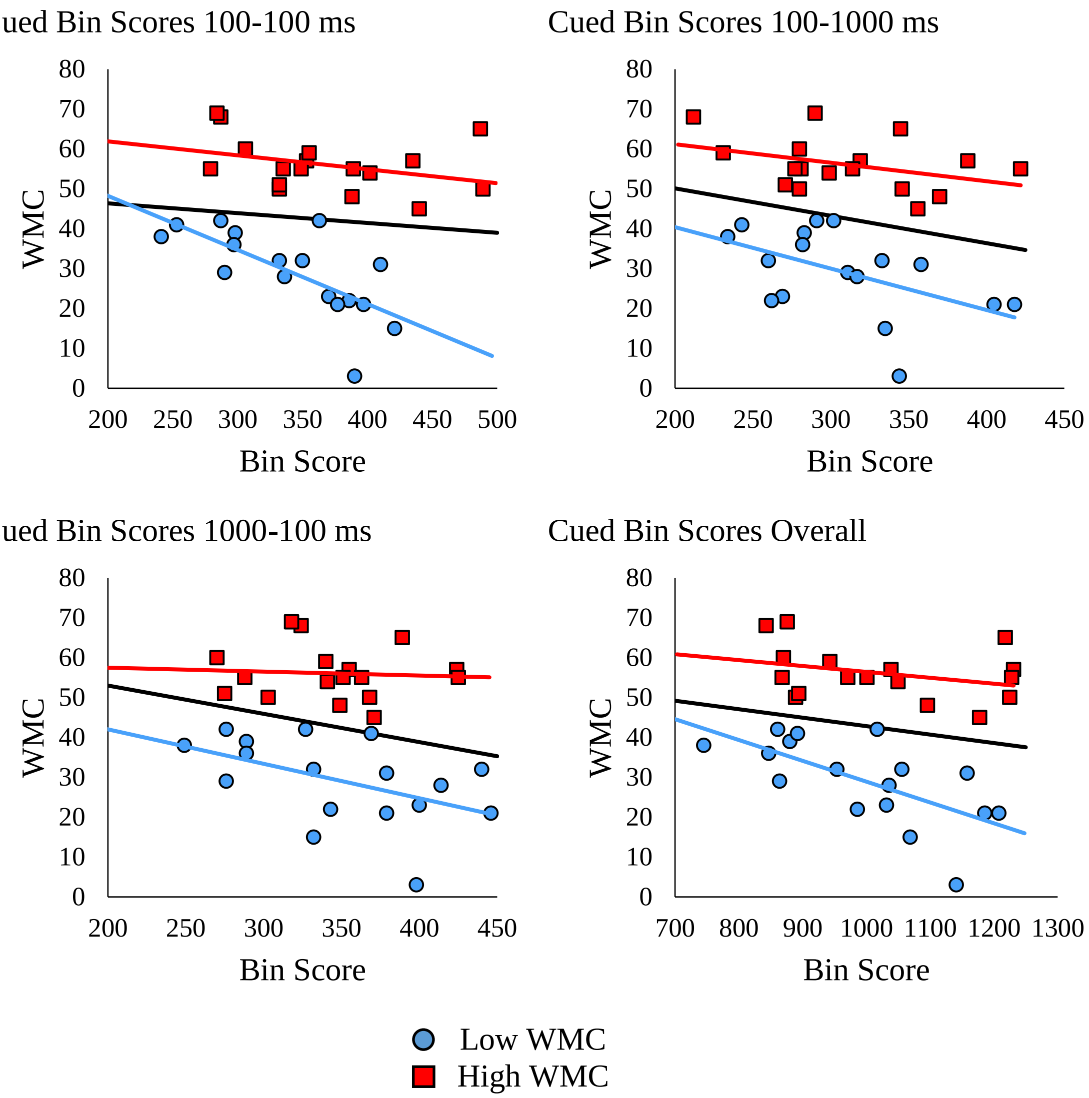


Figure 11. Scatterplots demonstrating the relationship between working memory capacity (WMC) and bin scores on the explicitly cued task switching paradigm. The relationship is shown for low and high WMC participants overall and across the three timing manipulations used in this switching paradigm. The centre line indicates the regression line for the full sample.

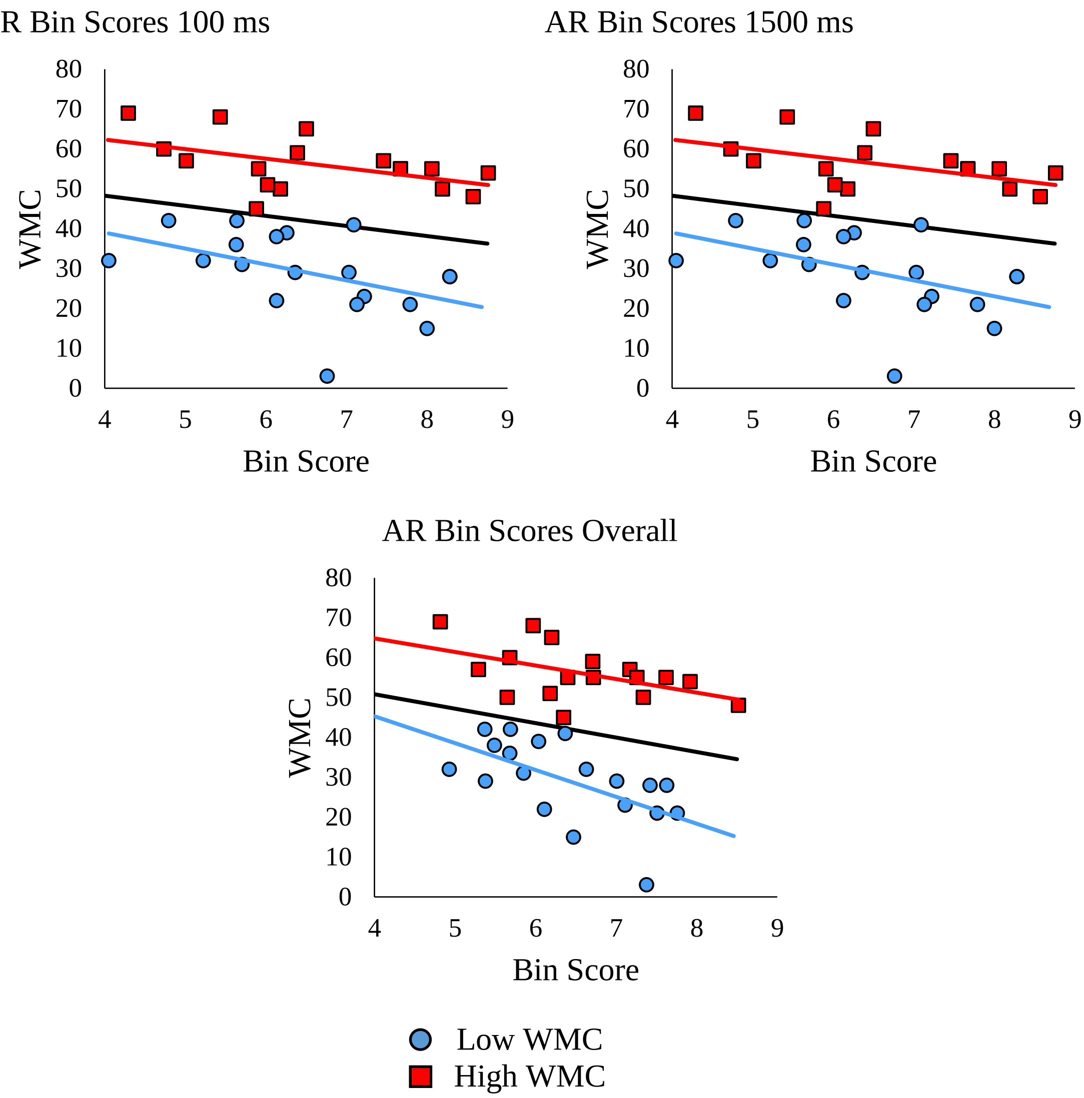


Figure 12. Scatterplots demonstrating the relationship between working memory capacity (WMC) and bin scores on the alternating runs (AR) paradigm. The relationship is shown for low and high WMC participants overall and across the two timing manipulations used. The centre line indicates the regression line for the full sample.

2.3.3.3 Exploratory coefficient of variation analyses.

The relationship between WMC and CoV was also examined separately for high and low WMC participants. Once again, a stronger relationship between WMC and switch costs was found in the low WMC participants. For the explicitly cued paradigm, the only significant correlation to emerge was in the 100-100 ms timing condition, *r* (15) = -.49, *p* = .045, but the correlations overall (*r* (15) = - .46, *p* = .06), and in the 100-

1000 ms (*r* (15) = -.44, *p* = .08) and 1000-100 ms (*r* (15) = -.40, *p* = .11) conditions did fall in the expected direction but failed to meet statistical significance with an alpha level of .05. For high WMC participants in the explicitly cued paradigm, no relationship between WMC and switch costs were found overall (*r* (15) = -.13, *p* = .62) or in any of the timing conditions (100-100 ms: *r* (15) = .003, *p* = .99; 100-1000 ms: *r* (15) = .12, *p* = .64; 1000-100 ms: *r* (15) = -.43, *p* = .08). In the AR and VTS paradigms, no significant correlations were found between CoV and WMC in either the low or high WMC participants, however, the relationships were much stronger and in the expected direction in low WMC participants, which was not the case for high WMC participants.

For the AR task, for low WMC participants, correlations with WMC were as follows, overall: *r* (17) = -.36, *p* = .13; 100 ms: *r* (17) = -.26, *p* = .29; 1500 ms: *r* (17) = -.36, *p* = .13. For high WMC, correlations were still in the expected direction, but were smaller; overall: *r* (15) = -.13, *p* = .61; 100: *r* (15) = -.02, *p* = .93; 1500 ms: *r* (15) = -.24, *p* = .35. For the VTS, this same pattern emerged. For low WMC participants, correlations with WMC were not significant, but were in the expected direction, overall: *r* (16) = -.46, *p* = .05; 100 ms: *r* (16) = -.38, *p* = .12; 1000 ms: *r* (16) = 0.35, *p* = .16. For high WMC participants, the correlations were much smaller, and not always in the expected direction, overall: *r* (13) = -.08, *p* = .78; 100 ms: *r* (13) = .12, *p* = .68; 1000 ms: *r* (13) = -.20, *p* = .48. The CoV results, although not significant do follow the same pattern of results of the RT switch costs and bin scores, with the low WMC participants showing a stronger relationship between WMC and task switching and high WMC participants showing little or no relationship between these constructs (See Figure A-3 and Figure A-4 for scatterplots of these relationships).

2.4 Discussion

2.4.1 Working memory capacity and task switching.

The aim of this study was to explore the relationship between WMC and task switching using a variety of task switching paradigms. The amount of environmental support and timing parameters within the switching paradigms were manipulated to examine their potential influence on this relationship. The findings have potential implications for theories of both task switching and WMC, and these implications will be discussed.

It was hypothesized that the relationship between WMC and switch costs would vary depending on the amount of environmental support available. With less environmental support, more top-down executive control would be required for task performance (Arrington & Logan, 2005) this should lead to stronger correlations with WMC. Each of the three task switching paradigms used differed with regards to how much environmental support was available. No support was found for this hypothesis. There was clear evidence of switch costs in all three of the task switching paradigms, with participants showing slower reaction time and poorer accuracy on switch trials as compared to repeat trials. However, those switch costs were not related to WMC in any of the task switching paradigms. The magnitude of the correlations were fairly similar across the three task switching paradigms, but slightly larger in the VTS. The findings suggest that the amount of environmental support does not appear to have a strong influence on the relationship between WMC and switching.

The second research question aimed to examine whether timing parameters used in the switching task had any bearing on the relationship between WMC and switch costs. Timing was manipulated in the explicitly cued task switching paradigm by including blocks that allowed for time to prepare for the upcoming trial (RCI-CSI 100-

1000 ms), blocks that did not allow for preparation (RCI-CSI 1000-100 ms), and blocks that did not allow for preparation and also had added time pressure (RCI-CSI 100-100 ms). There was evidence that the timing manipulations had an effect as participants benefitted from having extra time available for preparation. Switch costs were smallest in the 100-1000 ms blocks as compared to the other two timing conditions. In the VTS and un-cued AR paradigm timing was manipulated by including both a long and short timing condition. This timing manipulation was effective in both paradigms, with participants showing significantly smaller switch costs when more time was available between trials.

It was hypothesized that the relationship between WMC and switch costs would be strongest when there was more time pressure. It was also predicted that an increase in the magnitude of the relationship between WMC and switch costs would be seen when there was no time available for preparation. Although the timing manipulations appear to have been effective, they did not have an impact on the relationship between WMC and task switching. On the explicitly cued task switching paradigm, we failed to find a relationship between WMC and RT switch costs and bin scores in any of the timing conditions. Similarly, in the VTS and un-cued AR paradigms, there was no relationship between WMC and switch costs or bin scores in either the short or long timing conditions.

2.4.2 Theoretical interpretations.

After examining the first two research questions using the traditional switch cost scoring method, we can conclude that there is no evidence of a relationship between WMC and switch costs. This relationship could not be found using any of the task switching paradigms which differed in the amount of environmental support that they offered or under any of the timing conditions examined. From a theoretical perspective, these findings are unexpected and surprising. The executive attention theory of WMC argues that WMC reflects attentional processes, including the ability to control attention and maintain information in active state (Engle, 2002, 2018; Engle & Kane, 2004; Kane, Conway, et al., 2007). High levels of WMC would allow for goal maintenance, and the retrieval of information even when distraction is high (Kane, Conway, et al., 2007). Task switching theories make similar statements about what happens during a switching task, stressing the importance of executive attentional control (Monsell, 2003). When participants switch between tasks, they use endogenous control to perform task-set reconfiguration. Task-set reconfiguration can include a variety of processes, such as shifting the focus of ones attention to the currently relevant task, as well as keeping goal states active and retrieving them when necessary (Monsell, 2003). From a theoretical perspective, the executive attention theory of WMC and the task-set reconfiguration theory of task switching argue that both of these tasks reflect endogenous attentional control processes. This is what led to the expectation that a relationship between WMC and task switching should exist.

However, given previous empirical research in this field, our findings are not particularly surprising. All previous studies examining the relationship between WMC and switch costs using traditional scoring methods and the alternating runs paradigm or some variation of the cued switching paradigm have failed to find any relationship between performance on these tasks (Gamboz et al., 2009; Hambrick & Altmann, 2015; Kane et al., 2003; Kane, Conway, et al., 2007; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003). So, our study did actually replicate the findings of most previous studies completed in this area. The only study to explore this relationship using the VTS did find a correlation between WMC and switch costs but only when a short RSI was used (Butler et al., 2011). We failed to replicate their findings.

There are a variety of potential reasons for why our results and those of previous studies failed to fit with what we would predict on a theoretical level. One possibility is that there is a flaw in the theoretical assertions of either the executive attention theory of WMC or the task-set reconfiguration theory of task switching. Let us first consider the executive attention theory. A variety of individual differences studies have provided extensive support for the idea that performance on complex span tasks reflects attentional control abilities. WMC has consistently been shown to be related to performance on attentional control tasks like the dichotic listening task (Conway et al., 2001; Furley & Memmert, 2012), the Stroop task (Kane & Engle, 2003; Unsworth et al., 2012), the anti-saccade task (Kane et al., 2001; Luo et al., 2017; Meier et al., 2018; Unsworth et al., 2012), the flanker task (Unsworth et al., 2012) and the go/no-go task (McVay & Kane, 2009b). This consistent and pervasive evidence and the fact that task switching stands out as an anomaly suggests that the lack of relationship between WMC and task switching doesn’t really offer enough evidence to suggest that WMC isn’t measuring attentional control in the way that has been proposed by the executive attention theory.

Instead, the problem may lie with task switching. This study has shown that the specific paradigm does not appear to be the problem. Fairly consistently, no relationship was found across the three task switching paradigms examined. However, there is reason to believe that the difficulty level of the switching task could have an influence on the relationship between WMC and task switching (Meier & Kane, 2017; Poole & Kane, 2009). We will return to this idea later in this chapter when we consider the results of the exploratory analyses and we will explore this proposition more thoroughly in Experiment 2 (Chapter 3).

Another possibility is that our switching task may not be measuring the kind of endogenous attentional control that we think it is. The compound-cue retrieval account of task switching argues that rather than using endogenous control processes to complete task-set reconfiguration, participants just do the same thing on each trial. They create a compound of the cue word and the target, and they use that compound to retrieve the correct response from long term memory (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Schneider & Logan, 2005). If participants complete the switching task in this way without recruiting any endogenous attentional control, then a lack of relationship between WMC and task switching would not be surprising. This model suggests that switch costs do not reflect the time needed to perform attentional control processes, but instead just reflect processes involved in cue switching. Every time the task switches, the cue switches, confounding these processes. Switch costs could just reflect cue encoding benefits on task repeat trials (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Schneider & Logan, 2005). Others have also suggested that this may be the reason why previous studies have failed to find a relationship between WMC and switch costs (Kane, Conway, et al., 2007).

In this study I attempted to try and explore the assertions of the compound-cue retrieval account by varying the amount of explicit cuing information available. It seems like the compound-cue retrieval account could only apply to the explicitly cued task switching paradigm. The un-cued AR paradigm and the VTS do not have explicit cues, so participants should not be able to form a compound of the cue and stimulus and retrieve the response without having to recruit endogenous attentional control processes. If the compound-cue retrieval model holds, and no endogenous control is required for successful task performance, then one would not expect a relationship between WMC and switch costs on the explicitly cued task switching paradigm. One would still expect endogenous control on the un-cued AR paradigm and the VTS because no explicit cues are available so it would be impossible to create a cue-stimulus compound.

The present study found no relationship between WMC and switch costs in any of the three paradigms, whether explicit cues were available or not. Surely the compound-cue retrieval model cannot account for all of these findings given the variability in use of cues across the paradigms. However, compound-cue retrieval might play a role in all three of the task switching paradigms that were used (Logan & Schneider, 2010). Participants may use internally generated cues to guide their task performance on both the un-cued AR and VTS paradigms (Logan & Schneider, 2010; Mayr, 2010). These internal cues would be combined with the stimulus to form compound cues that would be used to retrieve responses from memory. Given the design of the present study, I am unable to rule out the possibility that compound-cue retrieval accounts for the findings. Instead, future research will need to explore the relationship between WMC and switch costs when the cost of cue switching has been controlled for. This would isolate the component of switch costs that actually reflect endogenous attentional control. Experiment 3 (Chapter 4) will explore this idea in more detail using a 2:1 cue to task mapping paradigm.

2.4.3 Novel analysis techniques.

2.4.3.1 Bin scores.

It is also possible that the initial analysis failed to find a relationship between WMC and switch costs because of the switch cost scoring methods used. This brings us to the third research question which aimed to explore the role of switch cost scoring techniques in the relationship between WMC and task switching. It was hypothesized that if traditional switch cost scoring methods failed to reveal a relationship between WMC and task switching, which they did, perhaps more novel methods would allow such a relationship to emerge. No support was found for this hypothesis. Bin scores, which combined RT and ACC on the switching tasks showed increased reliability compared to the traditional switch cost methods, which replicated previous findings (Draheim et al., 2016; Hughes et al., 2014). However, these more reliable task switching scores still failed to show any kind of relationship with WMC. When switching was scored using this method, the relationship between WMC and task switching was similar to what was found with more traditional switch cost difference scores. This finding held for both the explicitly cued task switching paradigm and the un-cued AR paradigm. Only two studies have been completed examining the relationship between WMC and switching using combined ACC and RT analyses. Although one of them found a significant correlation between WMC and switching when this combined analysis was completed (Draheim et al., 2016), the other study still failed to find a relationship that reached statistical significance (Pettigrew & Martin, 2016). Given the novel nature of this research approach, it is not clear why we failed to replicate the findings of Draheim et al. (2016). It is possibly due to a lack of power, which we will discuss in more detail shortly. We will explore this possibility by replicating these analyses in a larger sample in Experiment 2 (Chapter 3).

2.4.3.2 Coefficient of variability (CoV).

A similar pattern of null findings emerged when the relationship between WMC and CoV on the task switching paradigm was examined. A relationship between these constructs was hypothesized because intraindividual variability is thought to be linked to fluctuating levels of attentional control. High WMC participants should be able to perform the task in a stable way, thus showing low RT variability. In contrast, low WMC participants, with poorer attentional control abilities would be likely to show greater fluctuations in that attentional control. However, I failed to find any evidence for this. Although this is the first study to examine this in the context of a task switching paradigm, the relationship between WMC and intraindividual variability on other attentional control tasks has been found in previous studies (Kane et al., 2016; Unsworth, 2015). These studies both took a latent variable approach and created attentional control factors comprised of CoV across a variety of attentional control tasks. Kane et al. (2016) examined a CoV attentional control factor created from performance on the sustained attention to response task, number Stroop, spatial Stroop, arrow flanker, and letter flanker. Unsworth (2012) created a CoV attentional control factor comprising scores on an antisaccade task, arrow flanker task, Stroop, and a psychomotor vigilance task. In both studies, intraindividual variability on these attentional control factors was significantly related to WMC. The failure to replicate such findings may be due to the fact that in the present study, intraindividual variability was examined on a single task rather than using a latent variable approach. The other possibility is that variability on the task switching paradigms that were used in this study do not serve as an index of attentional control. Overall, the novel analyses that we used to explore the relationship between WMC and task switching did not change the general conclusion that there does not appear to be a relationship between these constructs.

2.4.4 Task choice and congruency.

In addition to our three main research questions, two other factors that we explored were task choice on the VTS, and congruency effects on the other two switching paradigms. A relationship between WMC and task choice was hypothesized given the role that WMC appears to play in random number generation (Baddeley et al., 1998). However, no evidence of a relationship between WMC and task choice was found. This replicated the findings of the only other study to explore this question (Butler et al., 2011). It is possible that randomly generating numbers may be quite different from making task choice decisions in the context of a task switching paradigm. Perhaps task choice is not heavily reliant on WMC. When we are choosing which task to perform, there are a number of different sources of information available to guide that choice beyond just trying to follow the instruction to do each task 50% of the time and to switch between them (e.g., previous task choice, previous stimulus, current stimulus, etc.). Our final choice may depend on which of those sources is most prominent at a given moment when the decision is being made (Butler et al., 2011). If this is the case, there would be a variety of factors aside from WMC that would play a role in the task choice process. More research is necessary to explore the exact mechanisms involved in task selection on the VTS.

To my knowledge, this is the first study to explore the relationship between WMC and response congruency effects in the context of task switching. Given the novel nature of this research question, it was unclear whether a relationship between these constructs would be expected as different theories made different predictions about this. Across both our explicitly cued switching paradigm and the un-cued AR paradigm, significant congruency effects were found. However, those congruency costs were not related to WMC. These results support the activated LTM theory of congruency costs (Kessler & Meiran, 2010; Liefooghe et al., 2012; Meiran & Kessler, 2008). This theory argues that stimulus-response associations that underlie the congruency effect are held in the activated portion of LTM, which is not limited in capacity.

2.4.5 Exploratory findings.

The exploratory analyses which examined the relationship between WMC and task switching separately in high and low WMC participants yielded some interesting results. However, these findings should be treated with caution, as the subgroup analyses were underpowered and the analyses were not pre-registered. These should be considered as exploratory findings, and not over interpreted. If we consider the research questions again, but using this subgroup analysis, different conclusions are drawn. In low WMC participants, the expected negative relationship between WMC and task switching was found.

The subgroup analyses did not change the conclusions regarding research question one. This question addressed whether the relationship between WMC and task switching would differ depending on the amount of environmental support available. Just as in the full sample analysis, the magnitude of the correlations were fairly similar across the three task switching paradigms, and this was largely the case for both low and high WMC participants.

In contrast, the conclusions regarding research question two change quite dramatically when the subgroup analyses are considered. For low WMC participants, in the explicitly cued task switching paradigm, a significant correlation was found between WMC and RT switch costs in both the condition with increased time pressure (100-100 ms block), and the condition in which time was available for preparation before the next trial (100-1000 ms block). In the AR and VTS paradigms, in low WMC participants there was a significant relationship between WMC and RT switch costs in the conditions with increased time pressure, but not in the long timing condition when time was available for preparation. This provides some support for the hypothesis that WMC is related to task switching under the most taxing timing conditions. Interestingly, this pattern of results was only found in low WMC participants. High WMC participants showed no relationship between WMC and switch costs in any of the switching paradigms under any of the timing conditions. These findings offer some support for research question two, as the magnitude of the relationship between WMC and task switching appears to vary based on the timing parameters used.

Research question three hypothesized that a relationship may emerge when bin scores were used to examine performance on the switching paradigm rather than difference scores. In the subgroups, the bin score analysis largely replicated the effects of the difference score findings. However, when the bin score analysis was used, the magnitude of the relationship between WMC and switching was slightly larger than when traditional difference scores were examined. For low WMC participants, in the explicitly cued switching paradigm, WMC was significantly related to bin scores in all timing conditions. However, for high WMC participants, no significant correlations were found. In the un-cued AR paradigm, for low WMC participants, significant correlations were found in both timing conditions. For high WMC participants a significant relationship was not found in the long timing condition, but there was a significant relationship between WMC and bin scores in the short timing condition even for high WMC participants.

We were also able to replicate this finding of a stronger relationship in low WMC participants when we examined intraindividual variability. In low WMC participants, on the explicitly cued switching paradigm, CoV was significantly related to WMC in the condition in which time pressure was high. In the other timing conditions, the relationship between CoV and WMC did not reach statistical significance, but did come close. In contrast, in high WMC participants no relationship between WMC and CoV was found. In the AR and VTS paradigms, the same pattern of larger correlations between WMC and CoV in low WMC participants was found, although they did not reach statistical significance.

These findings were quite surprising. None of the previous studies that examined the relationship between WMC and task switching had examined the pattern of results in this way. It is possible that this is the reason that so many previous studies have failed to find a relationship between these constructs. That relationship may only exist in low WMC participants, and would be washed out when a full range of WMC's was used to explore the relationship. There are a variety of potential reasons for why this pattern may have emerged. We will first explore the role of Spearman's law of diminishing return before turning to the potential role that task difficulty may play in these findings.

2.4.5.1 Spearman's law of diminishing return.

If we consider Spearman's law of diminishing return, these subgroup findings are not particularly surprising. Spearman (1925) proposed that mental processes have a general law of diminishing returns. The correlation between general intelligence (*g*) and other cognitive abilities is smaller in individuals with higher IQ levels. Basic tasks of cognitive abilities are more highly correlated with both IQ and with one another in participants with low IQ scores as compared to those with high IQ. Similarly, different subtests of standard IQ tests, such as the WAIS-R and WISC-R, are intercorrelated more highly in low IQ subjects then in those with high IQ levels (Detterman & Daniel, 1989). This proposition that tests of various cognitive abilities are less correlated in high ability subjects has been replicated many times over the last 100 years, with a recent meta-analysis examining over 100 articles and concluding that there is evidence that the correlation among cognitive ability tests does decrease as overall abilities increase (Blum & Holling, 2017). This seems to be what we have found in the present study. The strongest correlations between WMC and task switching were found in the lowest ability participants and weak to no correlation was found in high ability participants. This law of diminishing returns is not restricted to tests of general intelligence or general cognitive abilities, but seems to extend to tests of specific executive functions, such as working memory (Redick et al., 2012; Redick & Lindsey, 2013).

The exact composition of the participant pool appears to have an important influence on the relationship between working memory tasks. The degree to which different complex span tasks are correlated varies depending on the participant sample, with smaller correlations in high ability university samples and stronger correlations in community samples (Redick et al., 2012). One study examined the impact of the participant sample on the relationship between performance on an n-back measure of working memory and a complex span measure of WMC. In a university subsample, they found the relationship between n-back and complex span tasks to be non-significant. However, when this relationship was examined in a subsample of community members, the correlations were significant (Redick & Lindsey, 2013). Redick & Lindsey (2013) suggested that this may be due to restrictions in range. In a university sample, you are unlikely to get as much variability as you would with a community sample which would likely comprise more diversity. This restricted range offered by university samples could really limit the magnitude of any correlations.

We used a university sample in the present study, so it is possible that our null findings in our overall sample are due to restrictions of range and our significant findings in our subsample analysis may be due to the law of diminishing returns. Although a number of the previous research studies which failed to find a relationship between WMC and switching have been completed in university samples (Hambrick & Altmann, 2015; Miyake et al., 2000; Oberauer et al., 2003), this hasn't always been the case. Other studies which also failed to find a relationship have used community samples (Gamboz et al., 2009) or combinations of community and university samples (Klauer et al., 2010; Pettigrew & Martin, 2016). In fact, one of the only studies to actually find a relationship between WMC and switch costs used a sample made up entirely of university students (Butler et al., 2011). Sample composition may play some sort of role in explaining the failure of previous studies (including the full sample analysis in the present study) to find a relationship between WMC and task switching, however it is unlikely to explain the entire story.

2.4.5.2 The role of task difficulty.

WMC and attentional control tasks are not related under all circumstances. Instead, the complexity or difficulty of the attentional control task seems to play an important role in determining exactly when a relationship will emerge. It is in situations that are rich in interference, requiring top-down control to maintain focus and block out distractions that a relationship between WMC and endogenous attentional control tasks tends to emerge (Meier & Kane, 2017). This relationship is only present when the need for cognitive control is especially high. The relationship between WMC and Stroop performance only emerges when the percentage of congruent trials is high (Engle, 2002; Kane & Engle, 2003). When congruency is 0%, high and low WMC participants perform the task equivalently. Under such circumstances, goal maintenance is fairly easy because you can use the same strategy on all trials; ignore the word, and name the ink colour. When congruency is 75%, goal maintenance is far more difficult. It is easy to just read the word, so it can be easy to forget that you are actually supposed to be naming the ink colour. Under such circumstances, low WMC participants make twice as many errors as high WMC participants. These results suggest that differences between high and low WMC participants depend on the task situation, when the task is especially difficult, an association between cognitive control and WMC emerges.

Similar findings have come from studies examining the relationship between WMC and visual search tasks. Using a prototypical visual search paradigm, high and low WMC participants perform equivalently (Kane, Poole, Tuholski, & Engle, 2006). However, when the task is made to be more demanding on executive attention, by adding additional distractors, high WMC participants were able to complete the search task more rapidly than low WMC participants (Poole & Kane, 2009).

Context also influences the relationship between WMC and filtering. Filtering tasks assess one’s ability to focus on and maintain information in the face of distracting, irrelevant information. The relationship between WMC and filtering only emerges on more challenging tasks that really tax filtering (Robison et al., 2018). In a standard filtering task, in which participants had to remember what orientation red rectangles were in, while ignoring blue rectangles, there did not appear to be a relationship between WMC and filtering. However, in a second experiment designed to tax filtering by requiring participants to update which items they needed to pay attention to on a trial by trial basis, WMC was related to filtering performance. This second experiment would have taxed cognitive control more than the first, requiring moment to moment adjustments. It was only under this taxing condition that a relationship between WMC and attentional control was found.

The results of these studies suggest that the relationship between WMC and cognitive control is only evident when cognitive control is particularly taxed either by challenging goal maintenance (Kane & Engle, 2003) increasing distractors (Poole & Kane, 2009), or by requiring frequent updating of relevant and irrelevant information (Robison et al., 2018). Perhaps this is why we did not observe the relationship between WMC and switch costs in the entire sample in the present study. It is possible that the switching tasks used did not sufficiently challenge cognitive control in all participants. Instead, our results suggest that cognitive control was taxed in low WMC participants, thus eliciting the expected relationship between WMC and switch costs. These participants would have needed to recruit executive processes in full to perform the task successfully, and this revealed an association between WMC and switch costs.

Cognitive control may not have been sufficiently taxed in high WMC participants. Even though high WMC participants should have access to additional resources which they should recruit to perform the task better, if the task was not particularly challenging, they may have chosen not to recruit executive control resources completely. Using proactive cognitive control is metabolically demanding and costly (Braver, Gray, & Burgess, 2007). High WMC participants may reserve those resources for more challenging events they may encounter in the future (Barrett, Tugade, & Engle, 2004). We do not exert all of the cognitive control abilities we have available all of the time. Deciding whether to use cognitive control involves making a cost-benefit decision about whether to expend that extra effort (Kool, Shenhav, & Botvinick, 2017; Shenhav, Botvinick, & Cohen, 2013). We tend to try to minimize cognitive demand whenever possible. If high WMC participants were not challenged by the switching tasks used in the present study, they may not have needed to fully recruit their cognitive resources. This may be why we failed to find a relationship between WMC and switch costs in the high WMC subgroup.

In the exploratory findings, when bin scores were examined, in the explicitly cued switching paradigm, high WMC participants showed no relationship between WMC and bin scores. However, in the AR paradigm, under time pressure, high WMC participants did show a relationship between WMC and bin scores. This was the most challenging condition assessed using bin scores. The AR paradigm was challenging because it offered less environmental support than the explicitly cued paradigm. The short timing manipulation would have induced greater time pressure, and thus increased the difficulty of the task. Perhaps this increased task difficulty explains why this was the only condition under which we saw a significant relationship between WMC and task switching. To explore the role of task difficulty in the relationship between WMC and switch costs, Experiment 2 (Chapter 3) will vary the degree of difficulty of the switching paradigm by manipulating the context in which it is completed. This will shed some light on the role of task difficulty in the relationship between WMC and task switching.

2.4.6 Limitations.

This study has a number of limitations which should be noted. The most important limitation is the lack of power. It was underpowered, especially for conducting the subgroup analyses which split the sample into high and low WMC groups. This really limits the kind of conclusions that can be drawn from these findings. The subgroup analyses were both underpowered and unplanned so they should be considered exploratory in nature.

An important note is that the sample size used in this study is small. Individual differences research tends to demand large sample sizes (Schweizer, 2010). Our sample size was limited by practical reasons as participant recruitment for a two hour experiment proved challenging. University settings can often limit sample sizes in individual differences research and it can be quite challenging to find small relationships even with samples of 50-100 participants (Revelle, Wilt, & Allen, 2010). This is concerning for a variety of reasons. It is possible that our effect sizes in the sub-group analyses have actually been over-estimated as is often the case when small sample sizes are used (Yarkoni & Braver, 2010). Another factor that should be considered in our discussion of sample size is the reliability of our task switching measures. Bin scores were quite reliable, however RT switch costs only just reached acceptable levels of reliability, and ACC switch costs were not as close to reaching acceptable levels. The reliability of a measure can have an important impact on the sample size required, with a larger sample required for less reliable measures (Hedge et al., 2018; Yarkoni & Braver, 2010). Given the low reliability of our ACC switch cost measure and the borderline reliabilities of our RT switch cost measures, a larger sample size would be useful. Experiments 2 (Chapter 3) and 3 (Chapter 4) of this thesis will try to address these concerns by using larger sample sizes.

Another potential limitation of this study is that we counterbalanced the order of the task switching paradigms. This was done so that the order in which the switching paradigms were completed did not influence the results. For example, if everyone completed the explicitly cued paradigm immediately prior to the VTS, it may have influenced the probability of switching on the VTS. The explicitly cued switching paradigm has a 25% switch probability. It is possible that this would then influence how frequently participants chose to switch when they completed the VTS. To mitigate these kinds of order effects, the order in which the switching paradigms were completed was counterbalanced. However, this introduced a potentially important confound to our study. Counterbalancing is generally not recommended for individual differences research because it creates an important difference between participants, namely the order in which they completed the tasks (Draheim, Harrison, Embretson, & Engle, 2018). This added difference can make it more difficult to find a relationship between the variables of interest. Given the design of the current study, we cannot rule out whether task order may have had an influence on our results. None of the other studies in this thesis will use order counterbalancing to avoid this confound.

2.4.7 Summary and conclusion.

I failed to find a relationship between WMC and task switching when traditional switch cost analyses were completed and when analyses were completed using more novel scoring methods. These findings which replicate previous research are problematic for the executive attention theory of WMC and the task-set reconfiguration theory of task switching. Both of these theories would predict a significant relationship between performance on these tasks. However, when subgroup analyses were completed exploring the relationship between WMC and task switching separately in low and high WMC participants, a significant relationship between performance on these tasks was found. However, this relationship was only present in low WMC participants. No relationship was found in participants with high WMC. It has been argued that participants with low WMC likely needed to recruit all of their executive attention resources to perform the switching task, thus eliciting a significant correlation between WMC and task switching. High WMC participants may have found the switching tasks too easy, and they may not have needed to fully recruit their executive attention resources. I will explore this proposition further in Chapter 3. These results should be interpreted with caution given our small sample size and our lack of power for the subgroup analyses that were conducted.

Chapter 3 – Examining the Role of Task Difficulty in the Relationship between Working Memory Capacity and Task Switching

3.1 Objective

The majority of studies that have directly examined the association between task switching and working memory capacity (WMC) using complex span tasks have failed to find a relationship between performance on these tasks (Hambrick & Altmann, 2015; Kane et al., 2003; Kane, Conway, et al., 2007; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003). The results of Experiment 1 supported these previous findings, showing no relationship between WMC and switch costs. However, upon further exploratory examination, it became clear that while switch costs and WMC were not related in high WMC participants, there was a relationship between WMC and switch costs in the low WMC subgroup. The aim of this chapter is to replicate these initial findings, and examine them in more detail.

3.1.1 The role of task difficulty.

WMC and other cognitive control tasks are often not related under all circumstances. Instead, they are generally only related when the need for cognitive control is high. WMC tends to be related to attentional control in situations that include a great deal of distraction and interference, requiring the recruitment of top-down resources (Meier & Kane, 2017). This is evident for the relationship between WMC and the Stroop task. WMC is only associated with Stroop task performance when the percentage of congruent trials is high (Engle, 2002; Kane & Engle, 2003). Under these circumstances, goal maintenance is challenging, and this is the only condition which elucidates a relationship between WMC and Stroop performance.

Similarly, the relationship between WMC and visual search tasks emerge when additional distractors are added to the searching task (Poole & Kane, 2009). Such a relationship is not present in standard visual search tasks which lack distractors (Kane et al., 2006). Finally, the relationship between WMC and attentional filtering is only present when the filtering task is particularly taxing on cognitive control (Robison et al., 2018). See Chapter 2 for a more detailed examination of these findings. Across these studies, the relationship between WMC and attention is most prominent when cognitive control is taxed either by requiring goal maintenance (Kane & Engle, 2003), increasing the number of distractors (Poole & Kane, 2009), or by requiring frequent goal updating (Robison et al., 2018). Given these findings, this may offer an explanation for the common failure to find a relationship between WMC and task switching. Perhaps the task switching paradigms that have been used do not tax cognitive control enough for performance to show a relationship with WMC.

This task difficulty explanation may also explain the interesting pattern of results that emerged from the exploratory analyses in Experiment 1. Although a relationship between WMC and task switching was found in low WMC subjects, no such relationship emerged in high WMC participants. It is possible that those low in WMC were suitably taxed by the switching task and thus the expected relationship between WMC and switching was found. Those with high WMC may not have been sufficiently taxed by the switching task and this may explain why no relationship was found in this subgroup. Just because high WMC participants have access to greater attentional control resources does not mean that they will recruit them all the time (Barrett et al., 2004). In Experiment 1, they may have chosen to conserve their cognitive control resources for future use because the task was so simple. Following a cost-benefit analysis, high WMC participants may have decided not to expend any extra effort (Kool & Botvinick, 2014; Kool et al., 2017; Shenhav et al., 2013). If this is the case, increasing the difficulty of the switching task may encourage even high WMC participants to use more of their cognitive control resources to successfully complete the task. Under increased difficulty, the expected relationship between WMC and task switching may emerge.

To examine this possibility, the present experiment taxed cognitive control by increasing the level of difficulty of the task switching paradigm. The process of choosing how to increase task difficulty was a challenging one. It is important to carefully consider how task difficulty is manipulated as not all manipulations will impact distractor interference in the same way (Lavie, 2005; Lavie, 2010; Lavie, Hirst, de Fockert, & Viding, 2004). One option when considering increasing task difficulty is to increase the perceptual load of the task. The other involves increasing the load on cognitive control. It is only when the latter is manipulated that increases in distractor interference emerge. One’s ability to focus attention when faced with distractors declines when cognitive control is taxed (Lavie, 2005; Lavie, 2010; Lavie et al., 2004).

The goal for the present experiment was to increase the load on cognitive control resources during the switching task without fundamentally changing any aspect of the standard task or how it is performed. It was important to keep the switching task as similar as possible to the standard cued switching paradigm used in Experiment 1. To accomplish this, rather than altering the task itself to increase cognitive control load, the presence of distractors outside of the task was manipulated. In the present study, participants were required to complete the switching task while ignoring external auditory distractors. The explicitly cued paradigm from Experiment 1 was chosen because this task is so widely used in the task switching literature (Jost et al., 2013; Meiran, 2014).

Auditory distractions that are presented outside of the primary task have been shown to increase the difficulty level of the primary task and lead to decrements in performance (Ziegler, Janowich, & Gazzaley, 2018). This has been studied extensively using short term memory serial recall tasks with the irrelevant sound paradigm (Jones, Hughes, & Macken, 2010; Salame & Baddeley, 1982). The effect of auditory distraction has also been shown across other tasks, including tests of long term memory (Wais & Gazzaley, 2011), visual discrimination (Ziegler et al., 2018), prose memory (Sörqvist, 2010), reading comprehension (Sörqvist, Halin, & Hygge, 2010), mental arithmetic (Banbury & Berry, 1998), and the Stroop task (Cassidy & MacDonald, 2007). These studies used a range of auditory distraction stimuli, including ambient sounds from public areas like cafes (Wais & Gazzaley, 2011; Ziegler et al., 2018), office noises that include background speech (Banbury & Berry, 1998) or fictitious stories (Sörqvist, 2010; Sörqvist et al., 2010). Participants were instructed to ignore any auditory information, yet decrements in primary task performance were still observed. Tasks that tax working memory appear to be most vulnerable to impairment from auditory distraction (Campbell, 2005). Given that working memory is thought to play an important role in switching tasks, we would expect switching performance to be impacted by auditory distraction.

These findings fit well with Cowan’s embedded processes theory which argues that the focus of our attention is limited in capacity (Cowan, 1988, 1995, 1999). The addition of auditory distractors to a primary task will tax that attentional capacity, and tax our control resources. For example, office noises that contain speech have been shown to disrupt performance on a mental arithmetic task (Banbury & Berry, 1998). According to Cowan’s model, this disruption would take place because the constantly changing speech would capture attention and take it away from the primary mental arithmetic task. When the speech sounds capture attention, it depletes our attentional resources, leaving fewer resources for the arithmetic, and performance suffers. A number of studies have found support for the idea that auditory distraction captures our attention, thus leaving less attention available for the primary task (Bell, Dentale, Buchner, & Mayr, 2010; Körner, Röer, Buchner, & Bell, 2019). Auditory distraction should also tax cognitive control as participants will need to use control resources to focus their attention on the primary task and inhibit the response to distractors. In the present experiment, using auditory distraction to tax cognitive control resources should force all participants to fully recruit their attentional control resources to complete the switching task successfully.

3.1.2 Mind wandering.

Another factor that this experiment was interested in examining was mind wandering. A consideration of WMC variations in mind wandering during the switching task may provide some insight into the results of Experiment 1. This section will begin by describing what mind wandering is and how it is measured followed by a discussion of the link between mind wandering and WMC and the implications this may have for the findings of Experiment 1.

Mind wandering is extremely common, with estimates that during laboratory-based tasks, participants can spend 15-50% of their time mind wandering (Smallwood & Schooler, 2006). Any psychology experiment that is completed in the laboratory will involve some element of mind wandering on the part of the participant (Smallwood & Schooler, 2006). Given its ubiquitous nature, it is imperative that we, as psychological researchers, consider the effects of mind wandering. This term and area of study were largely neglected by mainstream psychology in the 20th century (Smallwood & Schooler, 2006). However, more recently there has been a growing interest in the topic, with a significant rise in the use of the term mind wandering since 2006 (Callard, Smallwood, Golchert, & Margulies, 2013). Although this research field has rapidly grown, both the definition of mind wandering, and measurement tools for assessing mind wandering are extremely heterogeneous (Callard et al., 2013; Weinstein, 2018).

Deciding on an exact definition of what constitutes mind wandering has been a challenge for the field, with studies using the term to describe a wide variety of mental processes (Christoff et al., 2018; Seli et al., 2018). For the purposes of this experiment I will use the definition of mind wandering as a shift in attention away from the current task to internal thoughts and feelings unrelated to the task (Smallwood & Schooler, 2006, 2015; Unsworth & McMillan, 2014). The most common way to investigate mind wandering is to use the probe caught method (Smallwood & Schooler, 2006, 2015; Weinstein, 2018). This involves interrupting participants at intermittent points while they are completing a task to ask them what they are thinking about at that given moment. Participant responses are taken into account to determine whether their thoughts were on-task or whether they were mind wandering.

One particular theory argues that mind wandering is a result of failures in executive attentional control (McVay & Kane, 2009a, 2010). According to this theory, mind wandering occurs when our executive control systems fail to successfully deal with interference from our internal thoughts. Such a theory would predict that individuals with less effective executive control (e.g., low WMC) would have more of these kinds of failures. Indeed, this does seem to be the case. A negative correlation has been found between WMC and mind wandering, with low WMC participants spending more time mind wandering than high WMC participants when they are completing demanding tasks (Kane & McVay, 2012; McVay & Kane, 2009a; Randall, Oswald, & Beier, 2014; Robison et al., 2018; Unsworth & Robison, 2016).

An interesting finding for the present experiment is that the relationship between mind wandering and WMC is not the same in all environments and instead seems to be mediated by task difficulty. Low WMC participants mind wander more only when the task is particularly difficult (Ju & Lien, 2018; Kane, Brown, et al., 2007; Rummel & Boywitt, 2014). Kane, Brown, et al. (2007) had participants carry around a personal digital assistant for a week, which would prompt them to report what they were doing and thinking at different intervals each day. They were asked if their mind was wandering from the activity that they were performing. The researchers found that lower WMC subjects had more task unrelated thoughts, but only when the task they were performing was reported to be challenging and require deep concentration. In contrast, there was no difference in mind wandering between high and low WMC participants when tasks were rated as unchallenging.

These findings have been replicated in the laboratory in two studies which looked at the relationship between WMC and mind wandering on an n-back task which manipulated load (Ju & Lien, 2018; Rummel & Boywitt, 2014). Low WMC participants had more task unrelated thoughts, but only when the task was particularly demanding. In contrast, when an easy, undemanding task was performed, either no relationship between WMC and mind wandering was found (Ju & Lien, 2018) or a positive correlation was found with high WMC participants actually showing more mind wandering than low WMC participants (Levinson, Smallwood, & Davidson, 2012;

Rummel & Boywitt, 2014). Task difficulty appears to have an important impact on the relationship between WMC and mind wandering.

Given the interesting relationship between WMC, mind wandering, and task difficulty, an examination of mind wandering during the switching task is a useful addition to this experiment. This relationship may help to explain the findings of Experiment 1. If the standard cued switching task used in Experiment 1 was not particularly challenging, high WMC participants may have allowed their minds to wander. If they were not fully focussing on the task, and recruiting their executive resources, this may explain why Experiment 1 failed to find a relationship between WMC and task switching in the high WMC subgroup. After all, in less demanding tasks, high WMC participants do tend to show more mind wandering than low WMC participants (Levinson et al., 2012; Rummel & Boywitt, 2014). The present study examined mind wandering by presenting thought probes periodically throughout the switching task. These probes required participants to indicate their current thoughts and whether their mind was wandering. This allowed for an examination of the rate of mind wandering in the standard switching task without auditory distraction and in the switching task in the presence of auditory distraction.

3.1.3 Aims and hypotheses.

This experiment has two primary aims. The first aim is to replicate the findings of Experiment 1 in a larger sample as Experiment 1 was underpowered for performing subgroup analyses. To achieve this, the relationship between task switching and WMC was examined in the present experiment using the same WMC task as Experiment 1 and the explicitly cued task switching paradigm with no external distractors (standard task switching condition).

The second primary aim of this experiment is to explore the relationship between task switching and WMC in more depth by examining the role of task difficulty. To achieve this, participants completed the explicitly cued task switching paradigm in the presence of auditory distraction (distraction condition). This allowed for an examination of the relationship between WMC and task switching when cognitive control was especially taxed. Finally, the relationship between WMC and mind wandering was also examined during the switching task to see if this varied across the two task difficulty conditions. This was done to provide more insight into the exploratory findings of Experiment 1.

With regards to the first aim, when the standard version of the switching task is completed, I expect to replicate the findings of experiment 1. It is hypothesized that no relationship between task switching and WMC will be found when the full sample is examined. However, using subgroup analyses, I expect to find a significant negative correlation between WMC and task switching in low WMC participants because in the standard task switching condition, their attentional control resources would be taxed by the task. In contrast, I do not expect to find any relationship in high WMC participants. In this standard task switching condition, the task may not be challenging enough to require high WMC participants to fully recruit cognitive resources.

With regards to the second aim, I would expect the results to be different when executive control is taxed. Previous studies have shown that the relationship between WMC and cognitive control only emerges when executive attention is particularly taxed (Kane & Engle, 2003; Poole & Kane, 2009; Robison et al., 2018). Given these findings, I hypothesize that under distraction condition, a relationship between WMC and task switching will be found in the entire sample and in both low and high WMC participants when they are examined separately.

In low WMC participants I would expect to see the relationship between WMC and switch costs in both the standard and distraction conditions of the switching paradigm as their executive control resources will be challenged in both circumstances. Previous studies have found that the performance of low WMC participants is not influenced by the addition of cognitive load in the form of a secondary task (Kane & Engle, 2000; Rosen & Engle, 1997). Scores may not change in low WMC participants because their performance is already maximally impacted under the standard switching condition (Ahmed & De Fockert, 2012; Kane & Engle, 2000; Rosen & Engle, 1997). In contrast, I would expect to see a change in scores in high WMC participants when a distraction is added (Kane & Engle, 2000; Rosen & Engle, 1997). For high WMC participants, no relationship would be expected between WMC and switching in the standard switching task. However, in the distraction condition, I would expect to see a significant negative correlation between switch costs and WMC. This condition should tax even the high WMC participants, and require them to fully recruit their executive control resources to perform the task successfully.

Finally, with regards to mind wandering, I would expect that under the standard task switching condition, higher mind wandering rates would be found in high WMC participants (Levinson et al., 2012; Rummel & Boywitt, 2014). In this condition, high WMC participants who are not taxed by the switching task will have resources available to allow their minds to wander. However, in the distraction condition, higher mind wandering rates are expected in the low WMC participants (Ju & Lien, 2018; Kane, Brown, et al., 2007; Rummel & Boywitt, 2014). Under such circumstances, low WMC participants are more likely to suffer from failures in executive control, and should thus show more mind wandering (McVay & Kane, 2009a, 2010).

3.2 Method

3.2.1 Pre-registration.

This experiment was pre-registered at the Open Science Framework (OSF) and the pre-registration can be accessed at the following link: https://osf.io/q54gt/?view_only=f2ad65cc2cea4d5d96b9e567d13c57f2. The study was powered to look at our primary analysis of interest which was the correlation between WMC and task switching. An a priori sample size analysis using G*Power version 3 (Faul et al., 2007) suggested that a sample of 67 would be necessary to detect an effect size of 0.3 with an acceptable error rate (alpha = .05, beta = .20). The two previous studies that found a relationship between WMC and task switching found effect sizes of .26 and .49 (Butler et al., 2011; Draheim et al., 2016).

3.2.2 Design.

This study used a within subject correlational design. The difficulty of the switching task was manipulated by having participants complete some blocks under auditory distraction and other blocks in the absence of any external distraction. All participants completing the switching task both in the presence and absence of auditory distractions. Timing parameters were also manipulated in the task switching paradigm. In addition to looking at the full sample, subsample analyses were also completed examining low and high WMC participants separately. A variety of dependent variables were measured (see Scoring section below).

3.2.3 Participants.

Sixty-six participants were recruited from around the Manawatu campus of Massey University (47 female; age: $M = 20.20$; $SD = 2.52$). One participant was excluded from the analysis for failing to meet 80% accuracy on the math portion of the WMC task and one participant was excluded because they chose not to perform the switching task. This left 64 participants for the analyses. All participants reported normal colour vision and hearing.

3.2.4 Apparatus and stimuli.

Apparatus information and stimulus descriptions for the WMC task and the switching task is identical to that described in Chapter 2.

The stimuli for the auditory distraction task were word lists recorded with a sampling rate of 44 100 Hz and an amplitude resolution of 16 bit. All words had a frequency in the English language of at least 15 per million words of text in the British National Corpus (Keuleers, Lacey, Rastle, & Brysbaert, 2012) and in SUBTLEX$_{\mathrm{US}}$ (Brysbaert & New, 2009). Auditory stimuli were presented through stereo headphones. Words were recorded in a female voice and were presented at a rate of approximately 48 words per minute at the same amplitude. To prevent participants from entraining their responses to the switching task with the presentation of the to-be-ignored words, words were presented at varying onsets. On average, a word was presented every 1.25 s, with a range of 1-1.5 s. There were 624 words in total, 312 monosyllable and 312 disyllabic words were used. Unrelated words were presented simultaneously to each ear and were matched for number of syllables and letters. See Figure 13 for examples.

3.2.5 Materials and procedure.

Each participant completed the WMC task first followed by the switching task. Order of task completion was not counterbalanced as counterbalancing is not recommended for individual differences research (Draheim et al., 2018). Participants were tested individually. The entire session lasted 70-80 minutes.

3.2.5.1 Operation span task.

The same operation span task that was used in Experiment 1, and described in Chapter 2 was administered in this experiment.

3.2.5.2 Explicitly cued task switching paradigm.

The method for the explicitly cued task switching paradigm was the same as Experiment 1, with a few minor modifications, see Figure 13. Task cues were presented for 100 ms or 1000 ms, depending on the block. Only two of the timing manipulations from Experiment 1 were used in Experiment 2 to reduce administration time. The response-to-cue interval (RCI) was held constant at 100 ms. Participants completed 8 experimental blocks of 97 trials. Four blocks were completed using the standard task switching paradigm without any external distractions and four blocks were completed in the presence of auditory distraction. Standard and auditory distraction blocks were interleaved. Half of the standard and distraction blocks had a cue-to-stimulus interval (CSI) of 100 ms, while the other half had a CSI of 1000 ms. These timings were interleaved. Instructions and stimulus-response reminders were presented before each block.

Before completing the eight experimental blocks, participants completed two 16 trial single task practice blocks, and two 32 trial switching practice blocks. On the first practice block, they performed the colour task on all trials, with a CSI of 1000 ms. On the second block, they performed the shape task on all trials with a CSI of 100 ms. On the third practice block, participants switched between performing the shape and colour tasks just as in the experimental blocks with a CSI of 100 ms. Finally, in the final practice block, participants performed the switching task in the presence of auditory distraction, with a CSI of 1000 ms. These practice blocks allowed participants to become familiar with the stimulus-response mappings, and to practice in each of the timing situations that would be presented in the experimental blocks. During the practice blocks reminders of the stimulus-response mappings were available at the bottom of the screen. These reminders were removed before the experimental trials began.

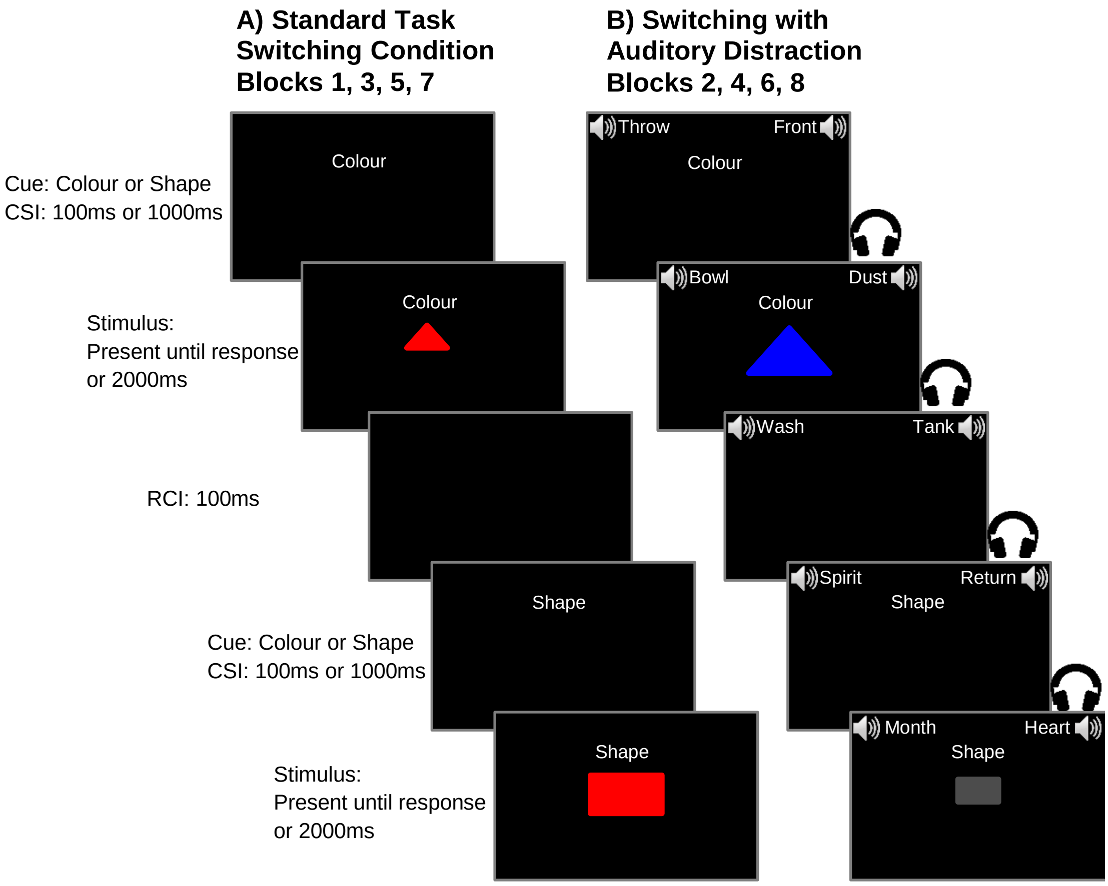


Figure 13. The trial sequences for each condition of the switching task. A) On the standard version of the switching task, a cue was presented on each trial instructing participants of which task should be performed on the upcoming stimulus. There were no additional external distractors present. B) For the auditory distraction blocks, participants completed the same switching task as in the standard version, but they were also wearing headphones and words were simultaneously presented to the two ears throughout the task. Participants were instructed to ignore the sounds. CSI: Cue-to-stimulus interval; RCI: Response-to-cue interval.

3.2.5.3 Auditory distraction.

It was important that the auditory distraction task be distracting enough to tax attentional control resources. To make it as challenging as possible, the auditory distraction task was administered dichotically. The dichotic listening task has been shown to index attentional control abilities (Conway et al., 2001; Furley & Memmert, 2012). The task involved the presentation of different words simultaneously to each ear. Rather than shadowing the words in one ear, as is customary on the dichotic listening task, participants were instructed to ignore the sounds completely. This modification was made as pilot testing revealed that participants struggled to respond to both tasks simultaneously. As such, the auditory distraction task had no response requirements. Instead, participants were just required to ignore the auditory information being presented and to focus on the primary switching task.

3.2.5.4 Mind wandering.

Mind wandering has been shown to vary depending on WMC, and the relationship between WMC and mind wandering is mediated by task difficulty (Kane, Brown, et al., 2007; Rummel & Boywitt, 2014). To investigate this construct, participants were asked to respond to probes that were presented randomly throughout the switching task. The probes were based on those used in previous studies (Kane et al., 2016; Levinson et al., 2012; McVay & Kane, 2009a). Each probe asked "What are you thinking about?" Participants were required to indicate exactly what they were thinking about in the instant before the probe was presented. They responded using the number keys on the keyboard to indicate whether they were thinking about *1) The task:* e.g., "I have to remember to press 1 because the cue is colour"; *2) Task Performance:* e.g., "Oh no, I did the last one wrong"; *3) Everyday things:* e.g., "That lecture this morning was boring"; *4) Current state of being:* e.g., "I'm hungry and tired"; *5) Personal worries:* e.g., "I'm scared that I won't have enough money for the phone bill", *6) Daydreams:* e.g., "I'm thinking of a flying horse"; *7) External environment:* e.g., "The lights are very bright"; *8) Other task-unrelated things*. The percentage of probes on which a participant reported mind wandering (responding with items 3-8) comprised their mind wandering score. Thought probes were randomly presented throughout the task switching paradigm at a rate of four probes per block, for a total of 16 mind wandering probes across the standard switching blocks and 16 probes in blocks which were completed with auditory distraction. Overall, 4% of trials were followed by a thought probe.

3.2.5.5 Self-report assessment of task difficulty.

At the end of the experiment, participants were asked to complete a difficulty questionnaire (see Appendix B). This questionnaire asked participants to indicate how difficult they found the switching task when they were performing it alone, how difficult they found the switching task when it was performed with auditory distraction, and finally, they indicated how difficult they found the WMC task. Participants responded to all three questions using a 7 point Likert scale ranging from very easy to very difficult.

3.2.6 Scoring.

3.2.6.1 Working memory capacity.

The main dependent variable from the operation span task was working memory span score. The absolute span score was calculated by examining the sum of all perfectly remembered sets. As one of the main goals of the experiment was to replicate Experiment 1, absolute span scores were examined. A median split was performed on WMC scores, as in Experiment 1. Two approaches were used to conduct the median split. The first used the median value (median = 42) from Experiment 1 in an attempt to replicate those findings. The second approach used the median value from the present experiment (median = 40) to provide equivalent numbers in both the high and low

WMC subgroups. Both approaches were analysed and the pattern of results were similar. Here, the results from the latter option will be presented as the group numbers were equivalent using this approach.

3.2.6.2 Task switching.

Difference scores. The main dependent variable for the task switching paradigm was difference scores in the form of switch costs. See Chapter 2 for a more thorough description. Smaller switch costs indicate better task performance.

The bin scoring method. The bin scoring method is an approach which combines both reaction time and accuracy into a single score. Please see Chapter 2 for a more detailed description. A smaller bin score is indicative of better performance.

Intraindividual RT variability. Intraindividual variability was examined by calculating a Coefficient of Variation (CoV = SD/M) for each participant. CoV was measured from repeat trials only to avoid confounding the experimental effect of interest (switch costs) with RT variability. See Chapter 2 for a more detailed discussion of RT CoV.

3.3 Results

For the switching task, the first trial from each block was excluded from all analyses. Trials following a mind wandering probe were treated the same as the first trial of each block and were also excluded from all analyses. Error and post-error trials were excluded from all reaction time analyses as were trials with reaction times less than 150 ms. Eliminating error and post-error trials led to the exclusion of 12% of trials from the switching task. Eliminating trials with an RT less than 150 ms led to the exclusion of 0.004% of trials. Switch and repeat trials were clearly defined before the experiment.

3.3.1 Task performance.

3.3.1.1 Task switching.

A 2 (trial type; switch versus repeat) x 2 (timing; CSI: 100 ms versus 1000 ms) x 2 (task difficulty; standard condition versus distraction condition) repeated-measures ANOVA was completed for both RT and ACC. The ANOVA's revealed a significant main effect of trial type, showing a significant switch cost for both RT, F (1, 63) = 191.12, $p < .001$, and ACC, F (1, 63) = 102.81, $p < .001$. Participants were slower and more error prone on switch trials (*M*±*SE*; RT: 852 ms ± 15; ACC: 90.1% ± 0.7) relative to repeat trials (RT: 724 ms ± 14; ACC: 94.6% ± 0.4). There was also a main effect of timing for both RT, F (1, 63) = 235.28, $p < .001$, and ACC, F (1, 63) = 45.00, $p < .001$. Participants were faster and more accurate on the CSI 1000 ms blocks (RT: 711 ms ± 15; ACC: 93.5% ± 0.4) when they had time available to prepare for the upcoming stimulus, as compared to the CSI 100 ms blocks (RT: 865 ms ± 14; 91.2% ± .6) when little time was available to prepare.

There was also a main effect of task difficulty for both RT, F (1, 63) = 11.48, $p = .001$, and ACC, F (1, 63) = 10.67, $p = .002$. However, the direction of this effect differed for RT and ACC. Unexpectedly, participants were actually significantly faster under the distraction condition (RT: 779 ms ± 14) than they were in the standard task switching condition (RT: 796 ms ± 14). While they may have been faster in the distraction condition, they were also less accurate (ACC: 91.8% ± 0.5) than in the standard task switching condition (ACC: 92.9% ± 0.5). It should be noted that while significant, the magnitude of the difference between the distraction condition and the standard task switching condition was very small for both RT and ACC.

The ANOVA also revealed some significant interactions. There was a significant trial type by timing interaction for both RT, *F* (1, 63) = 281.49, *p* < .001, and ACC, *F* (1, 63) = 13.37, *p* = .001. While switch costs were significant in both of the timing conditions (both p < .001), the magnitude of the switch costs differed. Both RT and ACC switch costs were smaller when participants had time available to prepare for the upcoming trial (CSI: 1000 ms) relative to when no time was available for preparation (CSI: 100 ms). Figure 14 provides a visual depiction of these interactions, showing the mean RT and ACC for task switch and task repeat trials in both of the timing conditions.

There was also a significant trial type by task difficulty interaction for ACC, *F* (1, 63) = 6.19, *p* = .02, although it was not significant for RT. Although there were significant switch costs in both the standard switching and distraction conditions (both *p* < .001), the magnitude of the switch costs differed. Accuracy switch costs were larger in the distraction condition than in the standard task switching condition. A visual depiction of this interaction can be seen in Figure 14c.

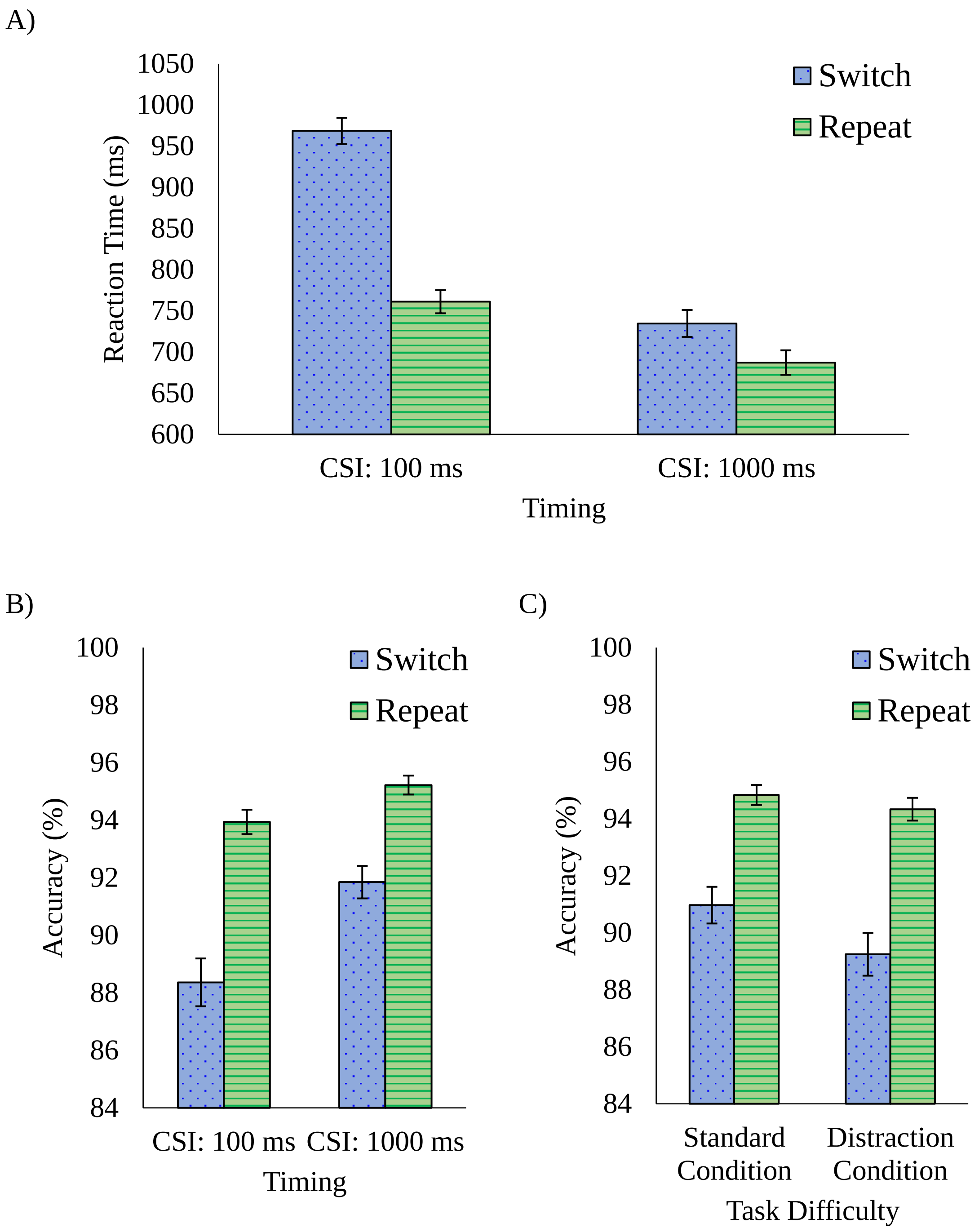


Figure 14. Mean reaction time (A) and accuracy (B and C) for each trial type. A) and B) offer a visual depiction of the interaction between trial type (switch vs repeat) and timing. C) offers a visual depiction of the interaction between trial type and task difficulty. CSI: cue-to-stimulus interval. Error bars indicate standard error of the mean.

Although the different pattern of results for RT and ACC regarding task difficulty could suggest that some sort of speed-accuracy trade-off was occurring, most of the results suggest a similar pattern of performance for both ACC and RT. Overall, RT and ACC in the task were significantly negatively correlated in both the standard task (*r* (62) = -.25, *p* = .002) and distraction conditions (*r* (62) = -.23, *p* = .03). This suggests that regardless of difficulty level, participants who were faster on the task also tended to be more accurate which would not suggest a speed-accuracy trade-off. We will return to this discussion below when we consider the impact of the manipulation check.

3.3.1.2 Working memory capacity.

OSpan Absolute span scores ranged from 3 to 75 (*M* = 38.53, *SD* = 17.70), and scores were normally distributed, *K-S* (64) = 0.06, p = .20. Partial span scores ranged from 18 to 75 (*M* = 56.20, *SD* = 12.23) and they violated the assumption of normality, *K-S* (64) = 0.14, p = .005. One of the main goals of this experiment was to conduct a replication of Experiment 1, so all results presented are for absolute span scores. Absolute span scores showed greater variability, which is useful for our individual differences approach and they did not violate the assumption of normality making them the optimal choice.

3.3.1.3 Manipulation check: Task difficulty.

The RT and ACC data described above showed that our manipulation of task difficulty, by adding the auditory distraction condition, did have the expected impact on the results. Participants were faster, but less accurate in the more difficult condition. For RT, there were no significant interactions between task difficulty and trial type, suggesting that task difficulty did not have a significant influence on RT switch costs. This was unexpected as it was predicted that the distraction condition would make the switching task more challenging, slowing reaction times and increasing RT switch costs. However, we did find a significant interaction between task difficulty and trial type for ACC, indicating that accuracy switch costs were influenced by the difficulty manipulation. Participants also self-reported the distraction condition to be significantly more challenging than the standard task switching condition.

A one-way repeated measures ANOVA on self-report task difficulty was statistically significant (*F* (2, 107.90) = 17.29, *p* < .001), see Figure 15. Participants rated the switching under distraction task to be significantly more difficult than the standard switching task (*p* < .001). The WMC task was also rated as more difficult than the standard switching task (*p* = .001). There were no significant differences in difficulty ratings between switching under distraction and WMC (*p* = .62). These findings suggest that from the participant's perspective, adding the auditory distraction task did make the switching task more challenging for them.

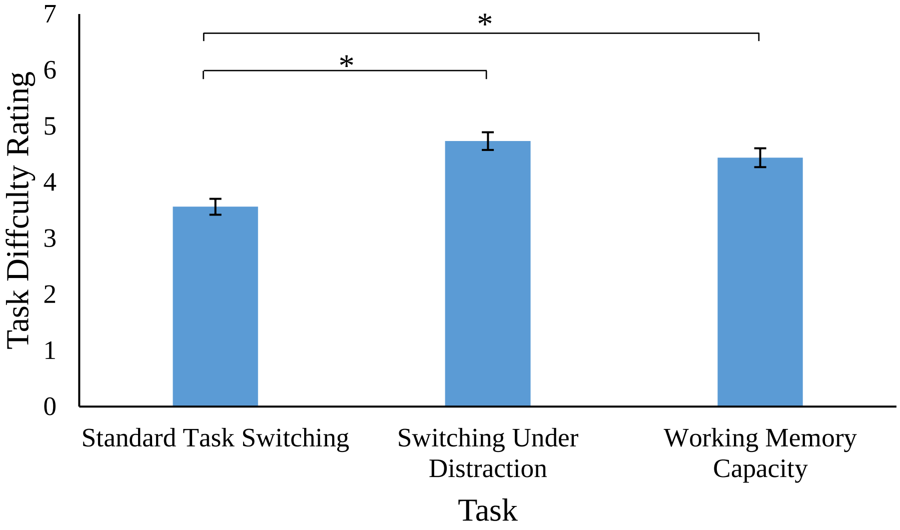


Figure 15. Self-report task difficulty ratings. Ratings were made on a 7-point Likert scale ranging from very easy (1) to very difficult (7). Error bars represent standard error of the mean.

3.3.2 Replicating Experiment 1: The association between working memory capacity and task switching.

To address the first aim of this experiment, which was to see whether the results of Experiment 1 could be replicated, the same analyses that were completed in Experiment 1 were repeated using only the blocks that administered the standard version of the task switching paradigm. The standard task blocks were similar to those used in the cued task switching paradigm in Experiment 1.

3.3.2.1 Full sample analyses.

The examination of task performance in the previous section revealed significant switch costs in the switching paradigm, showing a pattern of results that was similar to what was elicited in Experiment 1. To examine the relationship between WMC and task switching in the standard task version of the switching paradigm, a series of correlational analyses were completed. It was expected that the results of Experiment 1 would be replicated and that no relationship between WMC and switch costs would be found when the entire sample was examined.

Table 3 shows that some evidence to support a replication of Experiment 1 was found in the full sample. For RT, there was no relationship between WMC and switch costs overall, or in the 100-1000 ms condition. However, there was a significant positive correlation in the 100-100 ms condition. This is difficult to interpret as a negative correlation was expected (See Figure 16 for scatterplots of these relationships). This single finding should not be over-interpreted. ACC switch costs replicated the findings of Experiment 1 as no relationship was found between WMC and switch costs overall or in any of the timing conditions (See Figure C-1 for scatterplots of these relationships).

An analysis of bin scores and CoV replicated the findings of Experiment 1 in the full sample. There is no relationship between WMC and bin scores overall, or in either of the timing manipulations (see Table 3 and Figure 16). Similarly, in the full sample, there was no relationship between WMC and CoV in the task switching paradigm. WMC was not related to CoV overall, *r* (62) = -.16, *p* = .22, or the 100-100 ms, *r* (62) = -.06, *p* = .66, or 100-1000 ms, *r* (62) = -.14, *p* = .27 timing conditions. See Figure C-2 for scatterplots of these relationships.

Table 3

Task Switch Descriptive Statistics, Reliabilities, and Correlations with WMC in the Standard Version of the Cued Task Switching Paradigm

Measure	*M*	*SD*	Reliability	WMC *r*	*P*
Switch Cost RT (Switch – Repeat (ms))					
Overall Switch Costs	117	76	0.72	.19	.13
Switch Cost 100-100	203	98		.30*	.02
Switch Cost 100-1000	42	84		.15	.23
Switch Cost ACC (Repeat – Switch (%))					
Overall Switch Costs	3.9	3.7	0.30	-.14	.26
Switch Cost 100-100	5.0	6.0		-.15	.23
Switch Cost 100-1000	2.7	3.6		-.03	.81
Bin Scores					
Overall Bin Scores	654	103	0.72	.13	.29
Bin Score 100-100	339	74		.14	.28
Bin Score 100-1000	315	54		.14	.29

Note. Cronbach's alpha reliabilities were calculated across the 4 blocks of the experiment in which the standard version of the cued switching task was completed. All tests are 2-tailed. **p* < .05. WMC: working memory capacity; RT: reaction time; ACC: accuracy.

3.3.2.2 Subgroup analyses.

In the overall sample, the pattern of results is clear and mostly replicates the findings of Experiment 1. There is little evidence of any relationship between WMC and task switching. The next step was to examine whether the subgroup analyses from Experiment 1 could be replicated. Caution should be noted when interpreting these subgroup analyses as they are underpowered to detect an effect size of 0.3 with an alpha of 0.05 and a beta of 0.80. Instead, the subgroup analyses are powered to detect an effect size of 0.42 with an alpha of 0.05 and a beta of 0.05. A significant negative correlation was expected between WMC and switch costs in low WMC participants and no relationship was expected in high WMC participants. The median absolute span score was 40, so participants were split into a low WMC group (WMC score < 40, N = 32) and a high WMC group (WMC ≥ 40, N = 32). Descriptive statistics comparing the switch costs between high and low WMC participants along with correlations between switch costs and WMC are shown in Table 4.

Switch costs did not correlate with WMC in either high or low WMC participants. No relationships were found overall, or in either of the timing conditions. The same pattern of results was found for bin scores, with no significant correlations found between WMC and bin scores overall or in either of the timing conditions in low or high WMC participants. See Figure 16 for scatterplots of the relationship between WMC and RT switch costs and WMC and bin scores. See Figure C-1 for scatterplots of the relationship between WMC and ACC switch costs. The scatterplots display these relationships separately for low and high WMC participants and also include the trend line for the full sample. Finally, the same pattern of results was seen for CoV. The relationship between WMC and CoV was not significant in low WMC participants (overall: r (30) = .05, p = .78; 100-100 ms: r (30) = .11, p = .55; 100-1000 ms: r (30) = -

.14, *p* = .27) or high WMC participants (overall: *r* (30) = -.13, *p* = .47; 100-100 ms: *r* (30) = .05, *p* = .77; 100-1000 ms: *r* (30) = -.06, *p* = .75). See Figure C-2 for scatterplots of the relationship between WMC and CoV.

Across RT and ACC switch costs, bin scores, and CoV, the results are clear. No relationship was found between task switching and WMC in either WMC subgroup. This experiment failed to replicate the findings of Experiment 1.

Table 4

Task Switch Descriptive Statistics and Correlations with WMC in Low (WMC<40) and High (WMC≥40) WMC Subgroups in the Standard Version of the Switching Paradigm

Measure	*M*	*SD*	WMC *r*	*p*
Switch Cost RT (Switch – Repeat (ms))				
Overall Switch Costs				
Low WMC	96	59	-.01	.96
High WMC	137	86	-.11	.54
Switch Cost 100-100				
Low WMC	166	67	-.16	.38
High WMC	239	110	.05	.80
Switch Cost 100-1000				
Low WMC	29	75	.13	.48
High WMC	55	92	-.03	.88
Switch Cost ACC (Repeat – Switch (%))				
Overall Switch Costs				
Low WMC	4.2	3.9	-.13	.49
High WMC	3.6	3.4	-.15	.40
Switch Cost 100-100				
Low WMC	5.4	6.3	-.21	.25
High WMC	4.7	5.8	-.18	.32
Switch Cost 100-1000				
Low WMC	2.9	3.6	.90	.63
High WMC	2.5	3.8	.001	.99
Bin Scores				
Overall Bin Scores				
Low WMC	636	89	-.07	.69
High WMC	671	114	.03	.87
Bin Score 100-100				
Low WMC	322	68	-.18	.34
High WMC	355	77	-.20	.91
Bin Score 100-1000				
Low WMC	309	46	.12	.52
High WMC	321	61	.05	.79

Note. All tests are 2-tailed. **p* < .05. WMC: working memory capacity; RT: reaction time; ACC: accuracy.

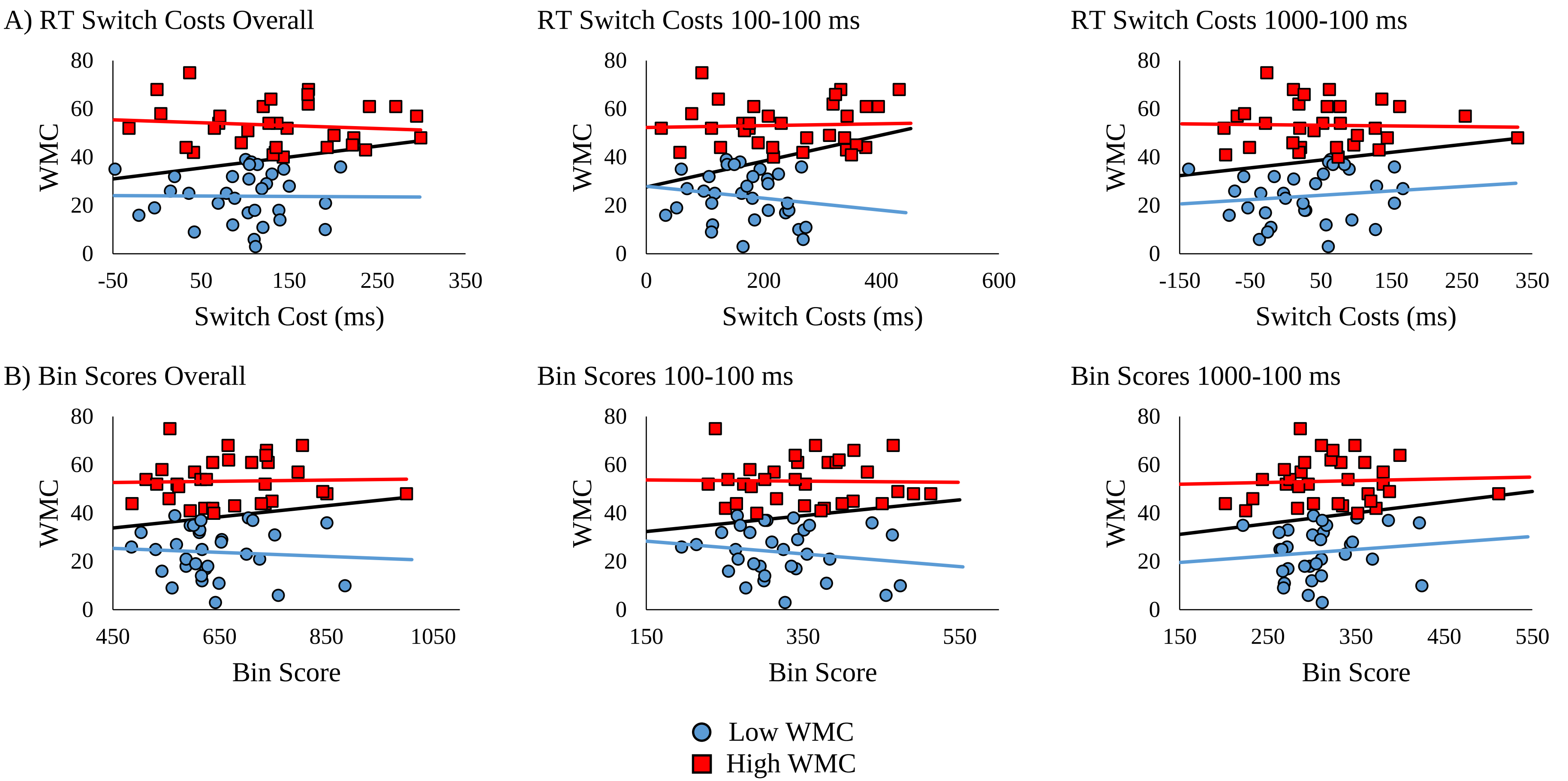


Figure 16. Scatterplots demonstrating the relationship between working memory capacity (WMC) and A) reaction time switch costs and B) bin scores on the standard version of the task switching paradigm. These relationships are shown overall and across the two timing manipulations used in the switching paradigm. The centre line indicates the regression line for the full sample.

3.3.3 Exploring the role of task difficulty on the relationship between working memory capacity and task switching.

To address the second aim of this experiment, task switching blocks that were completed under auditory distraction were examined. This allowed for an examination of whether increasing the difficulty of the switching task would have an impact on the relationship between WMC and task switching. The self-report results of task difficulty indicate that this manipulation led participants to report similar task difficulty ratings for the WMC and switching under distraction tasks. In contrast, the standard switching task was rated as being significantly easier than the other two tasks. These results suggest that the manipulation did make the task more challenging and brought it up to a similar difficulty level as the WMC task. It was expected that under this increased cognitive load, a significant negative relationship would be found between WMC and task switching in the entire sample and that this relationship would be seen in both low and high WMC participants.

3.3.3.1 Full sample analyses.

Table 5 shows the descriptive statistics of the switch costs and their correlation with WMC in the full sample when the switching task was completed with auditory distraction. For RT switch costs, overall, and in the 100-100 ms timing condition, switch costs were positively correlated with WMC. This finding is in the opposite direction to what was expected. Participants with high WMC performed worse on the switching task. This finding is counterintuitive and will be explored further in the discussion section. When ACC switch costs and bin scores were examined (see Table 5), no relationship was found between WMC and performance on the switching task. See Figure 17 for scatterplots of the relationship between WMC and RT switch costs and bin scores. See Figure C-1 for scatterplots of the relationship between WMC and ACC switch costs. The same pattern was found in the full sample for CoV. WMC was not related to CoV overall, r (62) = .11, p = .40, or in the 100-100 ms, r (62) = .12, p = .34, or 100-1000 ms, r (62) = -.01, p = .92 timing conditions (See Figure C-2 for scatterplots of these relationships). In the full sample, no support was found for the hypothesis that a significant negative relationship would be found between WMC and switch costs when the switching task was completed under additional cognitive load.

Table 5

Task Switch Descriptive Statistics, Reliabilities, and Correlations with WMC in the Auditory Distraction Version of the Switching Paradigm

Measure	*M*	*SD*	Reliability	WMC *r*	*p*
Switch Cost RT (Switch – Repeat (ms))					
Overall Switch Costs	130	78	.75	.28*	.023
Switch Cost 100-100	212	98		.25*	.049
Switch Cost 100-1000	53	81		.24	.06
Switch Cost ACC (Repeat – Switch (%))					
Overall Switch Costs	5.1	4.4	.36	.02	.86
Switch Cost 100-100	6.1	5.9		.01	.94
Switch Cost 100-1000	4.1	4.6		.03	.81
Bin Scores					
Overall Bin Scores	678	109	.78	.18	.17
Bin Score 100-100	351	71		.15	.25
Bin Score 100-1000	326	58		.22	.08

Note. Cronbach's alpha reliabilities were calculated across the 4 blocks of the experiment in which the switching paradigm was accompanied by auditory distraction. All tests are 2-tailed. * $p<0.05$. WMC: working memory capacity; RT: reaction time; ACC: accuracy.

3.3.3.2 Subgroup analyses.

Next, it was important to examine whether the relationship between WMC and switch costs varied for high and low WMC participants when the switching task was completed under distraction. It was expected all WMC participants would show a significant negative correlation. Caution should be noted when interpreting these subgroup analyses as they are underpowered to detect an effect size of 0.3 with an alpha of 0.05 and a beta of 0.80. Instead, the subgroup analyses are powered to detect an effect size of 0.42 with an alpha of 0.05 and a beta of 0.05. The descriptive statistics of switch costs and bin scores for high and low WMC participants along with correlations are shown in Table 6. ACC switch costs, RT switch costs, and bin scores all showed the same pattern of results. No relationship was found between WMC and task switching performance in either low or high WMC participants. See Figure 17 for scatterplots of the relationship between WMC and RT switch costs and WMC and bin scores. See Figure C-1 for scatterplots of the relationship between WMC and ACC switch costs. The scatterplots display these relationships separately for low and high WMC participants and also include the trend line for the full sample. Similarly, the relationship between WMC and CoV was not significant in low WMC participants (overall CoV: *r* (30) = .28, *p* = .12; 100-100 ms: *r* (30) = .22, *p* = .23; 100-1000 ms: *r* (30) = .17, *p* = .36) or high WMC participants (overall CoV: *r* (30) = .11, *p* = .55; 100-100 ms: *r* (30) = .15, *p* = .40; 100-1000 ms: *r* (30) = .05, *p* = .79). See Figure C-2 for scatterplots of the relationship between WMC and CoV.

Across RT and ACC switch costs, bin scores, and CoV, the pattern of results is the same. No relationship was found between task switching and WMC in either WMC subgroup. These findings did not support the hypothesis which predicted a significant negative correlation between these constructs when cognitive load was increased on the switching task.

Table 6

Task Switch Descriptive Statistics and Correlations with WMC in Low (WMC≤40) and High (WMC>40) WMC in the Auditory Distraction Version of the Switching Paradigm

Measure	*M*	*SD*	WMC *r*	*p*
Switch Cost RT (Switch – Repeat (ms))				
Overall Switch Costs				
Low WMC	104	65	.01	.97
High WMC	156	82	.01	.97
Switch Cost 100-100				
Low WMC	181	77	.002	.99
High WMC	242	109	-.05	.80
Switch Cost 100-1000				
Low WMC	31	76	-.02	.92
High WMC	74	81	.06	.73
Switch Cost ACC (Repeat-Switch (%))				
Overall Switch Costs				
Low WMC	4.9	3.9	-.25	.17
High WMC	5.3	4.9	.15	.41
Switch Cost 100-100				
Low WMC	5.9	5.4	-.26	.16
High WMC	6.3	6.5	.18	.32
Switch Cost 100-1000				
Low WMC	3.8	4.6	-.12	.52
High WMC	4.3	4.6	.07	.70
Bin Scores				
Overall Bin Scores				
Low WMC	657	95.5	-.13	.48
High WMC	698	119.6	.16	.37
Bin Score 100-100				
Low WMC	340	67.8	-.13	.50
High WMC	363	72.8	.16	.39
Bin Score 100-1000				
Low WMC	312	49.3	-.10	.58
High WMC	341	63.6	.14	.43

Note. All tests are 2-tailed. *$p < .05$. WMC: working memory capacity; RT: reaction time; ACC: accuracy.

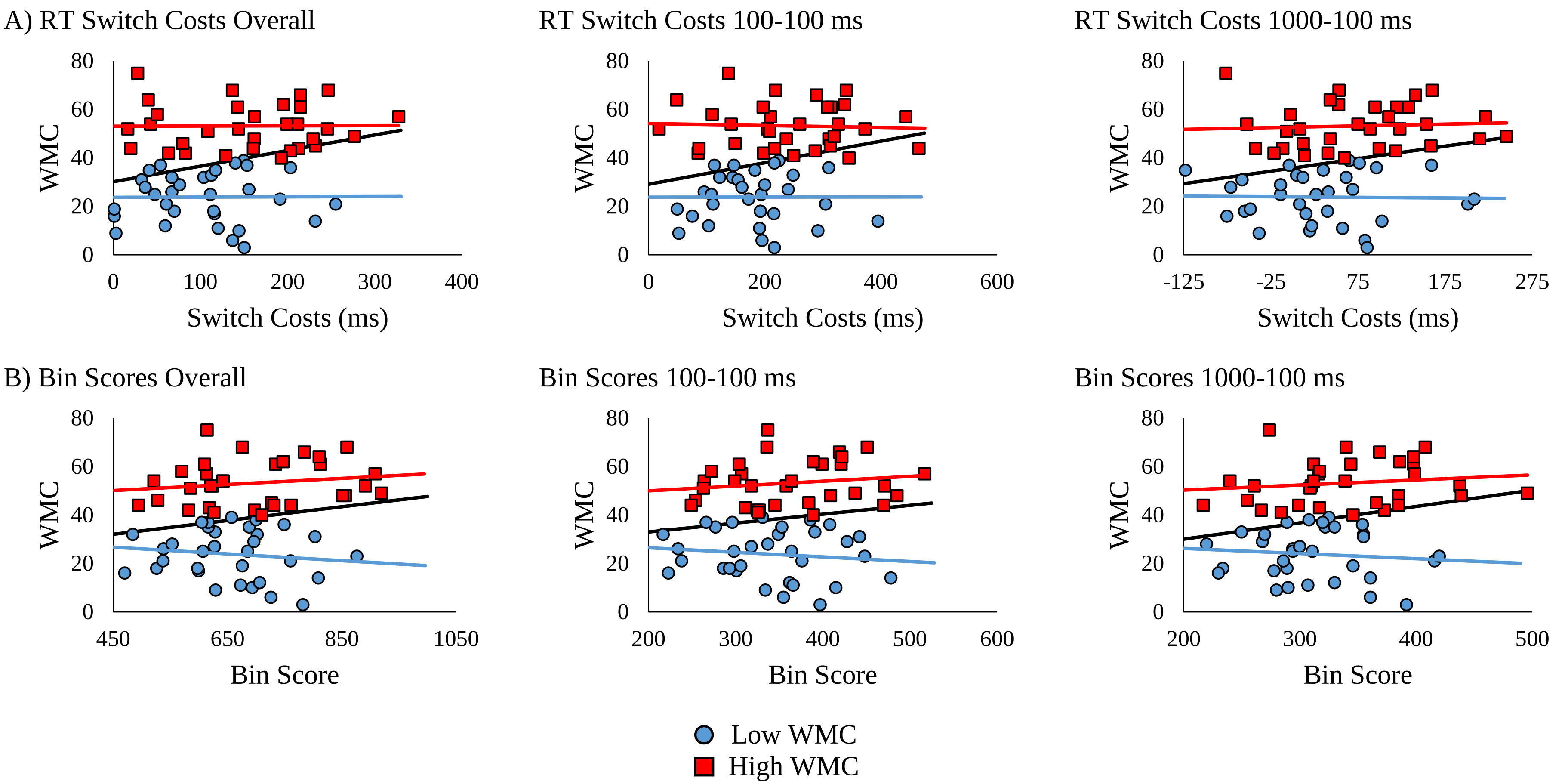


Figure 17. Scatterplots demonstrating the relationship between working memory capacity (WMC) and A) reaction time switch costs and B) bin scores on the auditory distraction version of the switching paradigm. These relationships are shown overall and across the two timing manipulations used in the switching paradigm. The centre line indicates the regression line for the full sample.

3.3.4 Congruency effects.

Response congruency was also examined on both the standard version of the switching task, and the version under auditory distraction. In the standard version of the switching task, there was evidence of congruency costs. Participants were significantly faster on congruent trials (RT: *M* = 741 ms, *SD* = 107) relative to incongruent trials (RT: *M* = 792 ms, *SD* = 119), t (63) = -12.10, p < .001. Similarly, participants were also more accurate on congruent trials (ACC: *M* = 96.4%, *SD* = 2.7) as compared to incongruent trials (ACC: *M* = 91.2%, *SD* = 4.2), *t* (63) = 13.86, *p* < .001. A similar pattern, with clear congruency costs was found on the switching paradigm accompanied by auditory distraction. Participants were significantly faster on congruent trials (RT: *M* = 722 ms, *SD* = 106) compared to incongruent trials (RT: *M* = 770 ms, *SD* = 110), *t* (63) = -12.65, *p* < .001. They were also more accurate on congruent trials (ACC: *M* = 96.0%, *SD* = 3.3) relative to incongruent trials (ACC: M = 90.0%, SD = 4.6), *t* (63) = 14.68, *p* < .001.

To examine whether there is a relationship between WMC and these congruency costs, a series of correlations were conducted. Given the findings in Experiment 1, a relationship was not expected between congruency costs and WMC but this is the first experiment to explore whether task difficulty has any effect on this relationship. RT congruency costs were calculated as incongruent RT minus congruent RT. ACC congruency costs were calculated as congruent ACC minus incongruent ACC. In the standard task version of the paradigm, WMC was not related to RT congruency costs (*M* = 51 ms, *SD* = 34; *r* (62) = -.12, *p* = .34; See Figure 18a) or ACC congruency costs (*M* = 5.2%, *SD* = 3.0; *r* (62) = -.01, *p* = .97), replicating the effects of Experiment 1. However, when the switching task was completed under distraction, a significant relationship was found between WMC and RT congruency costs (*M* = 48 ms, *SD* =

30.4; *r* (62) = - .33, *p* = .008). See Figure 18b for a visual depiction of this relationship. Participants with the highest WMC scores showed the smallest congruency effects. No relationship was found between WMC and ACC congruency costs (*M* = 6.1%, *SD* = 3.3; *r* (62) = -.12, *p* = .33).

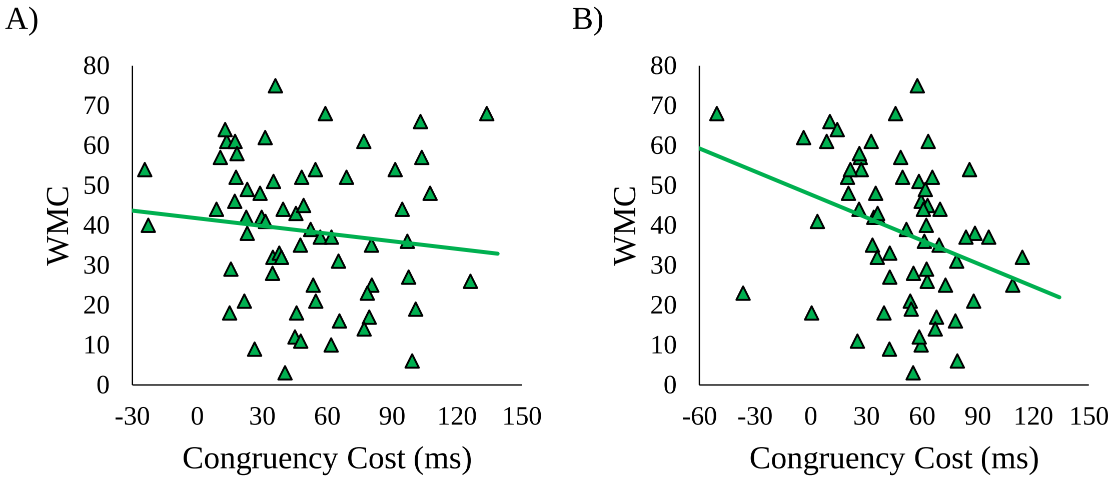


Figure 18. Scatterplots demonstrating the relationship between WMC and RT congruency cost. This is shown in A) the standard task switching paradigm and B) the task switching paradigm accompanied by auditory distraction.

3.3.5 Examining the role of mind wandering.

I expected WMC to be related to mind wandering during the switching tasks. Specifically, it was expected that in the standard task switching condition, higher mind wandering rates would be found in high WMC participants. When cognitive load was increased, as in the task switching under distraction condition, higher mind wandering rates were expected in low WMC participants. Mind wandering scores reflected the percentage of probes on which a participant reported mind wandering. To investigate this, a mixed-design ANOVA with task difficulty (standard versus distraction) as a within-subjects factor and WMC subgroup (low versus high) as a between-subjects factor was conducted. The data violated normality and the homoscedasticity assumption, so a square root transformation was completed. The outcomes of the untransformed and transformed ANOVA were similar. Here, I report the ANOVA outcomes using the transformed data. The ANOVA showed that there was no main effect of task difficulty, *F* (1, 62) = 1.21, *p* = .28, no main effect of WMC, *F* (1, 62) = 0.89, *p* = .35, and no significant interaction *F* (1, 62) = 1.25, *p* = .27. See untransformed descriptive data in Figure 19. The hypothesis was not supported. WMC did not have a significant impact on mind wandering during the switching task and this did not differ depending on task difficulty.

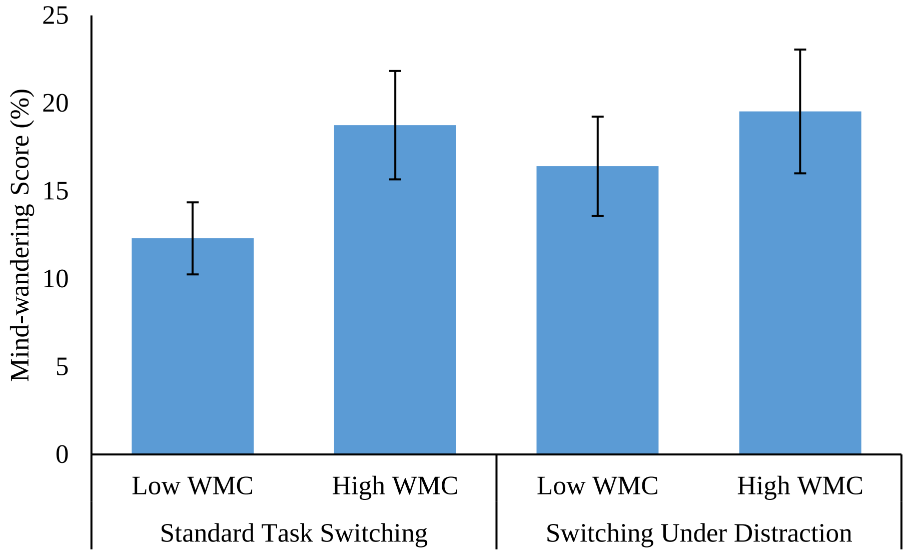


Figure 19. Mind wandering scores for low and high WMC participants in the standard switching paradigm and when task switching was completed under distraction. Higher mind wandering scores indicate more mind wandering. Error bars indicate standard error of the mean. WMC: working memory capacity.

3.4 Discussion

This experiment had two primary aims. The first was to replicate the results of Experiment 1 (Chapter 2) and the second was to explore the impact of task difficulty on the relationship between WMC and task switching. Clear switch costs were found in both the standard version of the switching task, and when it was completed under auditory distraction, however this experiment failed to find a relationship between WMC and task switching in either low or high WMC Participants. The findings of Experiment 1 were not replicated. Task difficulty had no effect on the relationship between WMC and switching. The relationship was similar when the standard switching task was completed, and under the more difficult condition in which auditory distractions were presented alongside the switching task. The results of this experiment raise additional questions about the relationship between these two tasks designed to measure executive functioning.

3.4.1 Replicating Experiment 1.

Experiment 1 (Chapter 2) found the expected negative relationship between WMC and task switching, but only in low WMC participants. In contrast, no relationship was found in the high WMC subgroup. The present experiment attempted to replicate these findings using a larger sample size. However, the findings were not replicated. Instead, no relationship between WMC and task switching was found in either low or high WMC participants.

In the full sample analysis, no relationship was found between WMC and task switching in Experiment 1, and similar findings emerged in the present experiment. Although, it should be noted that in both the standard and distracted switching tasks of the present experiment, a positive relationship between WMC and switch costs were found in some timing manipulations when RT switch costs were examined. This was surprising because the direction of the relationship is in the opposite direction to that which was expected. This suggests that those with high WMC actually performed worse on the switching task. Given the nature of the literature examining the relationship between WMC and switching, such a result is hardly surprising. This isn't the first time a significant, positive correlation has been found between WMC and RT switch costs (Draheim et al., 2016). However, when Draheim et al. (2016), used a more reliable measure of task switching performance, bin scores, the expected negative correlation between WMC and task switching emerged. When bin scores were examined in the present experiment, it did not lead to the expected negative relationship, but it did decrease the magnitude of the positive correlation and the relationship was no longer statistically significant. It should also be noted that across our other dependent variables, no relationship was found between WMC and task switching.

Taking all of these results into account, we have found no relationship between WMC and switching in low WMC participants or in high WMC participants, and in the overall sample, most evidence suggests a lack of relationship between these constructs. Rather than replicating Experiment 1, the results of this experiment replicate a great deal of previous work that has also failed to find a relationship between WMC and task switching under standard switching conditions (Gamboz et al., 2009; Hambrick et al., 2010; Kane et al., 2003; Kane, Conway, et al., 2007; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003). One reason for the inability to replicate the results of Experiment 1 may be due to the fact that the subgroup analyses were underpowered in that experiment, and the effect sizes may have been over-estimated. When a study is underpowered, it is less likely that a statistically significant result represents a true effect and effect sizes are often exaggerated under such circumstances (Button et al., 2013; Ioannidis, 2008). It seems likely that our exploratory findings from Experiment 1 reflect spurious results due to the small sample size.

3.4.2 The role of task difficulty.

Although we failed to replicate the findings of Experiment 1, it is still important to examine whether manipulating task difficulty had any impact on the relationship between WMC and switching. It was hypothesized that manipulating task difficulty would have an impact on the relationship between WMC and task switching, as previous research has shown that a relationship between WMC and other attentional control tasks emerges only when the need for cognitive control is high (Kane & Engle, 2003; Meier & Kane, 2017; Poole & Kane, 2009; Robison et al., 2018). To tax cognitive control, participants completed the switching task while also ignoring distracting auditory information. It was hoped that this additional taxing would force all participants to fully recruit their attentional control resources during task performance. Under such circumstances, a relationship between WMC and switching should emerge across all participants.

No support was found for this hypothesis. Instead, the results from the difficult condition mirrored those found in the standard version of the switching task. In the distraction condition, across all of the dependent variables that were examined, there was no relationship between WMC and task switching in low WMC participants, high WMC participants, or in the full sample. With the caveat of the positive correlation found between WMC and RT switch costs under some timing manipulations. See the section above for a discussion of this anomalous result. Unlike previous experiments which found changes in the relationship between WMC and visual search (Poole & Kane, 2009), filtering (Robison et al., 2018), and Stroop performance (Kane & Engle, 2003) when task difficulty was manipulated, the present study failed to find this pattern of results. The relationship between WMC and task switching did not change when cognitive control was especially taxed.

3.4.2.1 Was cognitive control sufficiently taxed?

It is possible that cognitive control was not sufficiently taxed in the present experiment for the relationship between WMC and task switching to emerge. Although participants reported the switching task accompanied by auditory distraction to be significantly more difficult than the standard switching task, and it had an influence on ACC switch costs, the task difficulty manipulation did not have a significant effect on RT switch costs. The magnitude of the RT switch cost was similar in both the standard task switching and distraction conditions of the task. It is important to consider whether auditory distraction, using the stimuli chosen in the present experiment, is a useful way of taxing cognitive control.

There is some debate in the auditory distraction literature regarding the degree to which distracting auditory stimuli tax endogenous control. Much of this debate has emerged from research using the irrelevant sound paradigm. This paradigm consists of a serial recall task requiring participants to remember sequences of items in the order in which they were presented. When to-be-ignored sounds are presented while participants perform this task, serial recall performance is impaired, and this is known as the irrelevant sound effect (Jones, Banbury, Tremblay, & Macken, 1999; Macken, Phelps, & Jones, 2009). In this paradigm, it has been shown that sound can have two different effects on serial recall. The changing state effect describes the findings that a changing stream of sound (e.g., RKLNP) will disrupt memory performance more than a sound stream which repeats (e.g., RRRRR) (Jones & Macken, 1993). The deviation effect describes the finding that sequences of sound with deviants (e.g., RRKRR) are more disruptive to memory performance than a repeating sound stream (e.g., RRRRR) (Hughes, Vachon, & Jones, 2007).

Debate arises around what mechanisms underlie these disruptions to task performance from auditory distraction. Some argue that both the changing state and deviation effect are caused by the same underlying mechanism; the capture of attention by auditory information (Banbury & Berry, 1998; Bell et al., 2010; Cowan, 1995; Körner et al., 2019). It is based on this theoretical proposition that the decision to use auditory distraction in the present experiment was made. This unitary account argues that all forms of auditory distraction should capture attention, and thus tax cognitive control.

However, others argue for a dual mechanism account of auditory distraction (Hughes, 2014; Hughes et al., 2007). This theory suggests that the changing state effect and deviation effect are distinct forms of auditory distraction, and only the deviation effect is caused by attentional capture. In contrast, the changing state effect results from conflict between the primary task and the auditory distractors. In the irrelevant sound paradigm, when changing state stimuli are used, both the primary serial recall task and the auditory distractors can involve the processing of order information. Processing the order information in the to-be-ignored auditory stream interferes with serial rehearsal, and task performance suffers. This theory argues that to-be-ignored sounds can impair primary task performance either by capturing attention, or by interfering with the processes required by the primary task.

Support for this dual mechanism account comes from studies showing that individual differences in WMC are related to the deviation effect but not the changing state effect (Hughes, Hurlstone, Marsh, Vachon, & Jones, 2013; Sörqvist, Marsh, & Nöstl, 2013; Sörqvist & Rönnberg, 2014). Such findings suggest that the deviation effect results from attentional capture and can be mitigated using ones attentional control resources. In contrast, the changing state effect does not appear to be controllable and may instead result from the involuntary processing of order information which interferes with the primary task. Further supporting this idea, although the deviation effect has been found across a variety of tasks, the changing state effect seems to be more task specific, primarily seen only in tasks that require serial rehearsal (Dalton & Hughes, 2014; Sörqvist & Rönnberg, 2014). The changing state effect is associated with perceptual abilities rather than cognitive control abilities, suggesting that changing state stimuli are only disruptive to primary task performance if they interfere with processes required by the primary task (e.g., serial rehearsal) (Sörqvist & Rönnberg, 2014).

It is difficult to say whether the auditory stimuli used in the present experiment would be considered similar to the stimuli used to assess the changing state effect. In the present study, participants heard constantly changing word lists, which is similar to the changing state stimuli, however they were presented dichotically, which makes the stimuli more similar to the dichotic listening paradigm, which is associated with WMC (Conway et al., 2001; Furley & Memmert, 2012). If the stimuli used were unintentionally having the same effect as changing state stimuli, then they would not elicit attentional capture, and would thus not tax cognitive control in the way that was intended. In that case, we would not expect them to impact primary task performance. Indeed, it was found that RT switch costs were not impacted by auditory distraction.

This suggests that we may not have taxed cognitive control enough with the auditory distraction stimuli. However, task performance was not entirely unaffected by the auditory distractors as participants were both faster, and less accurate on the switching task when it was completed under auditory distraction as compared to the standard switching task. It is difficult to know whether this impact on task performance resulted from the taxing of perceptual processing, with participants keeping track of the serial order of task performance (e.g., where they are in the sequence of switch and repeat trials) or whether it is due to a taxing of cognitive control due to attentional capture because of the dichotic nature of our auditory distraction stimuli.

3.4.2.2 Future manipulation of task difficulty on the switching paradigm.

Future research is needed in this area to further examine the impact of task difficulty on the relationship between WMC and task switching. Although participants rated the switching under distraction condition as more difficult than the standard condition, task difficulty did not have an impact on the relationship between WMC and switch costs. To be sure that this was not just due to the choice of task difficulty manipulation, it will be important for future research to examine the relationship between WMC and switching by altering the task difficulty on the switching task in slightly different ways.

Perhaps using auditory distraction stimuli which more closely map to the stimuli used to assess the deviation effect would be beneficial. Such stimuli have been shown to effect task performance across a variety of tasks, and the effect has been linked to individual differences in WMC. Deviating stimuli are thought to capture attention and thus tax attentional control. Under such circumstances perhaps we would be more likely to see changes in switch costs between the two task difficulty conditions. However, a variety of other auditory distraction stimuli have also been shown to impact primary task performance across a variety of primary tasks, including ambient sounds from public areas (Wais & Gazzaley, 2011; Ziegler et al., 2018), office noises and background speech (Banbury & Berry, 1998), and fictitious stories (Sörqvist, 2010; Sörqvist et al., 2010). When fictitious stories are used, high WMC participants are less distracted by the to-be-ignored stream of auditory information that those with low

WMC (Sörqvist et al., 2010). It does not seem like deviant sounds are the only option for taxing cognitive control using auditory stimuli. More research is needed into exactly which types of auditory stimuli tax cognitive control. Similarly, more research will be needed looking at the role of a wide variety of auditory distraction stimuli on switching task performance before we can make strong conclusions in this area.

3.4.2.3 ***Congruency costs.***

An interesting finding emerged when congruency costs were examined. No relationship was found between WMC and congruency costs in the standard version of the switching paradigm, replicating Experiment 1. However, when congruency costs and WMC were examined using the switching paradigm accompanied by auditory distraction, a significant relationship was found between WMC and RT congruency costs. Participants with the highest WMC scores showed the smallest congruency costs. Smaller congruency costs are indicative of better performance. Congruency costs reflect interference from the irrelevant response on incongruent trials, leading to slower responses compared with congruent trials (Liefooghe et al., 2012). Smaller congruency costs indicate that a participant is faster at overcoming such conflict. These findings support the executive attention theory of WMC which stresses the importance of WMC in overcoming conflict by inhibiting responses to strong, but irrelevant stimuli (Kane, Conway, et al., 2007). No other study to date, apart from Experiment 1 in the present thesis, has examined the relationship between WMC and the response congruency effect in the context of task switching.

There is some debate around the degree to which congruency costs reflect the limited capacity portion of working memory, with some arguing that they reflect stimulus-response associations and task representations in the activated portion of long term memory, which is not limited in capacity (Kessler & Meiran, 2010; Liefooghe et al., 2012; Meiran & Kessler, 2008). The results of this study, which shows a link between congruency costs and WMC suggest that to some degree, individual differences in congruency costs reflect differences in a limited capacity attentional control system. With those with more attentional control capacity (high WMC) showing smaller congruency costs, perhaps because they can more rapidly overcome the conflict between a previously relevant and a currently relevant response. The fact that we only see this effect under auditory distraction adds more weight to the argument that our auditory distraction stimuli likely did tax cognitive control to some degree. Such findings also fit with previous studies which only found a relationship between WMC and attentional control when control was particularly taxed (Kane & Engle, 2003; Poole & Kane, 2009; Robison et al., 2018).

3.4.3 Mind wandering.

The present experiment also examined whether different mind wandering rates in low and high WMC participants would help us to better understand the findings of Experiment 1. If high WMC participants showed more mind wandering in the standard switching task, this may help to explain why the expected relationship between WMC and switching was not found in that subgroup in Experiment 1. On the standard switching task, higher mind wandering rates were expected in high WMC participants, which would fit with previous studies (Levinson et al., 2012; Rummel & Boywitt, 2014). If high WMC participants are not fully taxed by the standard task, they may allow their minds to wander. On the more difficult switching with auditory distraction condition, it was expected that higher mind wandering rates would be found in low WMC participants, as has been found in previous research (Ju & Lien, 2018; Kane, Brown, et al., 2007; Rummel & Boywitt, 2014). Low WMC participants would be more likely to suffer from failures in executive control when the task was particularly taxing. No support was found for these hypotheses. WMC did not have a significant impact on mind wandering rates during the switching task when it was completed under standard conditions or under auditory distraction. There are a couple of possibilities for why this study may have failed to replicate these previous findings.

One important thing to consider is the fact that the relationship between WMC and mind wandering is generally quite small (Kane et al., 2016). Large scale studies using a battery of working memory tasks, and sample sizes of around 250 participants have found correlations around the $r = -.20$ range (McVay & Kane, 2009a; Unsworth & McMillan, 2014). Studies using only a single WMC task, and sample sizes more similar to the present study tend to find relationships that only reach marginal significance (Rummel & Boywitt, 2014), or they find no relationship at all (Krawietz, Tamplin, & Radvansky, 2012). These findings suggest that given the modest nature of the relationship between WMC and mind wandering, large sample sizes, and robust batteries of WMC tasks are important for detecting an effect.

Another factor to consider when investigating the relationship between WMC and mind wandering is the type of mind wandering that is occurring. Participants can engage in two different types of mind wandering while performing laboratory tasks; deliberate, intentional mind wandering and unintentional, unwanted mind wandering (Seli, Cheyne, Xu, Purdon, & Smilek, 2015). These two different types of mind wandering are dissociable at the neural level. Differences in cortical thickness and functional connectivity have been reported between those who self-report tendencies towards deliberate versus spontaneous mind wandering. Those who report a higher likelihood of deliberate mind wandering show enhanced integration between parts of the frontal parietal network (which is important for cognitive control) and the default mode network. In contrast, spontaneous mind wanderers showed less integrated connections between these networks, perhaps due to difficulties with attentional control (Golchert et al., 2017).

Especially relevant to the current study is the finding that only one of these types of mind wandering is related to WMC. Although low WMC participants have been shown to spontaneously mind wander more often, there is no relationship between WMC and deliberate mind wandering (Robison & Unsworth, 2018). The kind of task probes used in the present study do not allow for distinguishing between these two types of mind wandering. The switching task that participants completed was quite long, tedious, and fairly boring and there were no particular incentives offered for performance. This may have led to low motivation to perform the task well. Participants with lower levels of motivation have been shown to engage in more deliberate, intentional mind wandering (Robison & Unsworth, 2018; Seli et al., 2015). If motivation levels were particularly low, and intentional mind wandering was high, this may explain why no relationship was found between mind wandering and WMC. Such a relationship is only expected between WMC and unintentional mind wandering. It will be important for future research examining the relationship between WMC and mind wandering to consider motivation levels, and to distinguish between intentional, deliberate mind wandering, and unintentional, unwanted mind wandering. This can have an important bearing on the implications of the findings.

3.4.4 Theoretical interpretations.

In both the standard version of the switching task and in the switching task accompanied by auditory distraction, little evidence of a relationship between WMC and task switching was found in the present study. This was evident across a series of dependent variables used to measure switching performance, including RT switch costs, ACC switch costs, bin scores, and CoV. As discussed in Chapter 2, such null findings are problematic for a variety of theories, including the executive attention theory of WMC (Engle, 2002, 2018; Engle & Kane, 2004; Kane, Conway, et al., 2007) and the task-set reconfiguration theory of task switching (Monsell, 2003, 2017; Rogers & Monsell, 1995).

The executive attention theory of WMC asserts that WMC reflects that ability to control attention and maintain information in an active state (Engle & Kane, 2004; Kane, Conway, et al., 2007). Performance on WMC tasks requires endogenous attentional control processes and WMC scores reflect this. Similarly, the task-set reconfiguration view of task switching argues that task switching performance requires endogenous attentional control, and this should be reflected in the magnitude of the switch cost (Monsell, 2003; Rogers & Monsell, 1995). When performing a switching task, a task set must be adopted on each trial. A task set consists of all of the control settings that allow for stimulus identification, response selection and execution (Vandierendonck et al., 2010). On a switch trial, participants must reconfigure their task set to the appropriate task. This reconfiguration is a costly endogenous attentional control process and switch costs reflect the time needed to complete reconfiguration (Monsell, 2003, 2017; Rogers & Monsell, 1995). It is precisely because of the fact that WMC and task switching are both thought to measure executive attentional control processes that a relationship between these tasks is expected. However, the results of this thesis thus far have not supported this assertion.

Instead, it may be time to consider another theoretical proposition for explaining switch costs. Not all theories of task switching agree that some form of endogenous attentional control is necessary for task performance. The compound-cue retrieval account, which is described in Chapter 2 argues that switch costs do not reflect endogenous attentional control (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010). Switch costs emerge due to the fact that cue switching and task switching are confounded in the task switching paradigm. Each time the task switches, the cue also switches, and we must process the new cue. Poorer performance on switch trials, which we use as an index of attentional control abilities, may just reflect cue encoding benefits on task repeat trials (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Schneider & Logan, 2005). It will be important to try and separate out cue switch costs from task switch costs to better look at this confounding effect. We will explore these ideas in more detail in Experiment 3 (Chapter 4) of this thesis.

3.4.5 Limitations.

This experiment is not without its limitations, and these should be considered when interpreting the results. One limitation, which has already been discussed is the choice in manipulation of task difficulty used in the present study. It would be useful for future research to attempt to replicate these findings using different approaches to manipulating task difficulty.

3.4.5.1 Limitations of the task switching paradigm.

Another limitation that should be considered is that the traditional task switching paradigm was used in both Experiment 1 and 2. With this paradigm, cue switch costs cannot be separated from task switch costs, thus the degree to which cue switch costs are confounding task switching performance is not known (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Schneider & Logan, 2010). If the switch costs that have been measured are confounded by cue switch costs, it may explain why the relationship between WMC and task switching is so difficult to find. Previous research has already established a way of dissociating cue switch and task switch costs using the 2:1 cue to task mapping paradigm, which uses two cues for every task (For review, see Jost et al., 2013). Research completed using this paradigm has shown that although cue switch costs do exist, true task switch costs still account for a large portion of the slowing that takes place on switch trials (Mayr, 2010; Mayr & Kliegl, 2003; Monsell & Mizon, 2006). To address this limitation, and control for the confounding effects of cue switch costs, in Experiment 3 (Chapter 4), I will tease apart cue and task switch costs. A 2:1 cue to task mapping paradigm will be used to see if a relationship between switching and WMC emerges when the confounding effects of cue switching are taken into account.

3.4.5.2 Limitations of the working memory capacity task.

The limitations mentioned thus far have dealt with the task switching paradigm. However, it is also important to consider the choice of WMC task. The OSpan task was chosen because it is among the most widely used complex span tasks (Conway et al., 2005; Foster et al., 2015), and it has been used as the sole WMC measure in previous research examining the relationship between WMC and task switching (Butler et al., 2011; Hambrick & Altmann, 2015). A single WMC task was used to index WMC in the present research due to time constraints. However, the use of the OSpan as the sole measure of WMC reflects a limitation of the present study. Using only the OSpan to make conclusions about WMC performance is problematic because scores will contain variance from WMC, but also from the task itself, e.g., math ability, or speed at solving math problems. To avoid this problem, it is important to administer two or more complex span tasks and to create a composite score to measure the construct of WMC (Draheim et al., 2018; Foster et al., 2015). Taking this approach will lead to a more valid and reliable estimate of WMC.

In addition to the limitation of using only one complex span task, choosing the OSpan specifically, despite its widespread use, is also a limitation of this study. One reason that the OSpan is problematic is that it seems to show smaller relationships with a variety of other cognitive abilities when compared to other complex span tasks. It has even been argued that overuse of the OSpan in lieu of other task options has led to the failure to detect expected effects, or to find smaller effect sizes than would be expected (Draheim et al., 2018). This may help to explain why we have failed to find a relationship between WMC and task switching in the present study.

One of the reasons that the OSpan shows smaller effect sizes or null effects may be due to the fact that it is not successful at discriminating amongst high ability participants. Draheim et al., (2018) found that the OSpan was poor at discriminating amongst participants when their ability levels where higher than 0.5 standard deviations above the mean. This would be typical in an undergraduate student population such as the sample used in the present study. The authors went on to argue that the standard OSpan should not be used on entirely undergraduate samples for that reason (Draheim et al., 2018). There are a number of reasons why this task may be especially poor at discriminating among high ability subjects when compared to the other complex span tasks. This task has the simplest stimuli, which is likely to allow for rehearsal of the to-be-remembered items. On other complex span tasks, the stimuli consist of moving squares or arrows, which are far more challenging to rehearse than letters. In addition, mathematics is often quite automatic for undergraduate populations, and thus may not serve as the best task to block rehearsal (Draheim et al., 2018). Given these findings, it is important that research examining the relationship between WMC and other cognitive tasks, such as switching, use a variety of complex span measures. To address this, Experiment 3 (Chapter 4) will use three complex span tasks to measure the construct of WMC. To deal with the timing constraints that led to the initial choice of a single task, shortened versions of the complex span tasks will be administered (Foster et al., 2015).

3.4.6 Summary and conclusion.

The main aims of this experiment were to replicate the findings of Experiment 1 in a larger sample, and to explore the impact of task difficulty on the relationship between WMC and task switching. This experiment failed to replicate the subgroup analyses of Experiment 1, and must conclude that the exploratory results of that experiment were likely due to the underpowered sample that was used. With a larger sample size, I have now shown that there does not appear to be any relationship between WMC and task switching under standard, or more difficult task conditions. The next step will be to explore why we are continuing to find such null effects. Experiment 3 (Chapter 4) will examine the role of cue switch costs and will establish whether the relationship between WMC and task switching emerges when the confounding effects of cue switch costs are controlled for.

Chapter 4 – Exploring the Impact of Cue Switch Costs on the Relationship between Working Memory Capacity and Task Switching

4.1 Objective

In Experiment 2 (Chapter 3), no evidence of a relationship between working memory capacity (WMC) and task switching was found, replicating the results of a number of previous studies (Hambrick & Altmann, 2015; Kane et al., 2003; Kane, Conway, et al., 2007; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003). The aim of the present chapter is to explore whether this failure to find a relationship is due to the existence of cue switch costs. It has been suggested that to really tap into executive processes and be able to detect an association with WMC, task switching paradigms need to eliminate the role of cue encoding (Kane, Conway, et al., 2007). To examine this, a double cued task switching paradigm, with two cues for each task was used to isolate task switch costs from the confounding effects of cue switch costs. The 2:1 cue to task mapping paradigm has not previously been used to examine the relationship between WMC and task switching. The existence of cue switch costs may help explain why the results of Experiment 2 along with other previous research has failed to find a relationship between two important attentional control tasks; task switching and WMC.

4.1.1 Measuring cue switch costs and ‘true’ task switch costs.

There is some controversy and disagreement about what is actually measured by the task switching paradigm. The task-set reconfiguration account of switching argues that switch costs reflect executive control processes (Monsell, 2003; Rogers & Monsell, 1995). However, other authors have argued that switch costs do not reflect executive attention. Instead, they are merely the result of the confounding effect of cue switching. Every time the task switches, the cue also switches (e.g., from “colour” to “shape”), and every time the task repeats the cue also repeats (e.g., from “colour” to “colour”). Due to this confound, switch costs may reflect cue encoding benefits on task repeat trials (Logan & Bundesen, 2003, 2004; Schneider & Logan, 2005). The task cues are used to retrieve appropriate response information from long-term memory (LTM). However, before that can happen, the cue needs to be encoded. When the same cue is used on a subsequent trial (repeat trial), repetition priming leads to a facilitation of cue encoding processes. When cue encoding is faster, the retrieval of information from LTM will be faster, leading to better reaction time (RT) responses (Logan & Bundesen, 2003; Schneider & Logan, 2005). When the cue is switched, a new cue will need to be encoded, which will lead to slower RT on switch trials. Differences in encoding time between switch and repeat trials may explain the existence of switch costs. This suggests that endogenous attentional control may not be needed to perform the switching task, and in fact, task switch costs can be effectively reduced to cue switch costs.

To examine whether cue switch costs are present, Logan and Bundesen (2003) used a task switching paradigm with two cues for every task. They had participants switch between categorizing numbers by magnitude (less than 5 versus larger than 5) and parity (odd versus even). The magnitude task was cued with the words ‘magnitude’ and ‘high-low’ and the parity task was cued with the words ‘parity’ and ‘odd-even’. When this 2:1 cue to task mapping paradigm is used, instead of having the traditional two trial types (task switch and task repeat), three trial types emerge (See Figure 20 for a visual depiction of the three trial types). ‘No switch’ trials are the same as the traditional repeat trial, in which neither the task nor the cue switches (e.g., magnitude to magnitude). ‘Task switch’ trials are the same as in the traditional paradigm, with both the cue and the task switching (e.g., magnitude to parity). In addition, a new trial type emerges from this paradigm; ‘cue switch’ trials. On these trials, the cue switches, but the task remains the same (e.g., cue switches from magnitude to high-low) (Grange & Houghton, 2014; Jost et al., 2013; Logan & Bundesen, 2003). Using these three trial types, cue switch costs can be calculated. This also allows for the calculation of task switch costs after cue switch costs have been controlled for (See scoring section and Figure 21 for more detailed information on the calculation of these costs).

In their initial study, Logan and Bundesen (2003) found substantial cue switch costs (168 ms in experiment 3 and 95 ms in experiment 4). However, after these cue switch costs were controlled for, they found little remaining task switch costs (35 ms in experiment 3 and 14 ms in experiment 4). This finding suggested that the cue switching confound accounted for most of what we have traditionally considered task switch costs. Such a finding was concerning for the task-set reconfiguration account of task switching. Simultaneously, another lab was also investigating the impact of cue switching on task switch costs (Mayr & Kliegl, 2003). They too used a 2:1 cue to task mapping paradigm to control for the effects of cue switching, but they found very different results to Logan and Bundesen (2003). Although Mayr and Kliegl (2003) found large cue switch costs (298 ms in experiment 1 and 205 ms in experiment 2), they also found substantial task switch costs (302 ms in experiment 1 and 221 ms in experiment 2) after the cue switching had been controlled for. These findings suggest that cue switch costs do exist, and are an important confound in standard task switching paradigms, however ‘true’ task switch costs still remain after cue switching is controlled for.

This stark contrast in findings regarding the magnitude of ‘true’ task switch costs is concerning, and several studies set out to elucidate the reason for such a discrepancy. There are several aspects of the design of the task switching paradigm that have an important bearing on whether ‘true’ task switch costs are robust or not when cue switching is accounted for. One of these design features is switch probability. Low overall task switch probability, and lower probability of a task switch given a cue switch lead to larger ‘true’ task switch costs (Jost et al., 2013; Mayr, 2006; Monsell & Mizon, 2006; Schneider & Logan, 2006). In the experiment by Mayr and Kliegl (2003), the probability of a task switch was .33, and the probability of a task switch given a cue switch was .5. These probabilities were much higher in the experiment by Logan and Bundesen (2003), with a switch probability of .50, and the probability of a task switch given a cue switch was .67. Subsequent experiments have supported the idea that this experimental difference at least partially explains why Mayr and Kliegl (2003) found substantial ‘true’ task switch costs and Logan and Bundesen (2003) failed to (Mayr, 2006; Monsell & Mizon, 2006). If the probability of a task switch given a cue switch is particularly high (as in Logan and Bundesen (2003)), participants may begin to initiate a task switch whenever they detect a change in cue, before they have even processed the cue word (Mayr, 2006). This would lead to a reduction in ‘true’ task switch costs, given the advanced preparation to switch. It would also lead to an increase in cue switch costs because the task set which had been abandoned would have to be re-instated. There is evidence that participants do take such an approach and modulate their performance based on the probability of switches (Mayr, 2006). To encourage participants to only reconfigure their task set once the cue has been presented, the probability of a task switch given a cue switch needs to be kept low. Under such circumstances, task-set reconfiguration (in the form of ‘true’ task switch costs) can still be measured using the task switching paradigm (Monsell & Mizon, 2006).

In addition to trial type probabilities, the choice of cue used in the experiment also has an important impact on the magnitude of ‘true’ task switch costs. ‘True’ task switch costs are larger when arbitrary cues are used, as in the case of Mayr and Kliegl (2003) rather than explicit word cues, as in the case of Logan and Bundesen (2003) (Jost et al., 2013; Logan & Bundesen, 2004; Logan & Schneider, 2006). However, using arbitrary cues adds an additional task to the paradigm. One must interpret the cue, and this could be an additional confound on the results. Given this, even though ‘true’ task switch costs are larger with arbitrary cues, easy to interpret, explicit cues are recommended when attempting to measure task-set reconfiguration using the 2:1 cue to task mapping paradigm (Monsell & Mizon, 2006).

These findings suggest that it is not as easy as we first thought to measure task-set reconfiguration and index attentional control using the task switching paradigm. Instead, a variety of methodological issues need to be considered when designing such experiments. Monsell and Mizon (2006) have recommended a specific recipe for measuring task-set reconfiguration. They recommend using at least two cues per task to de-confound task switching and cue switching. They also recommend keeping the response-to-stimulus interval (RSI) constant and to vary the cue-to-stimulus interval (CSI) to allow for a clear examination of preparation. They suggest keeping the probability of a task switch low to encourage participants to engage in task-set reconfiguration only after the cue has been presented. Finally, they suggest using cues that are easily interpreted and to provide instructions that encourage participants to prepare for the upcoming stimulus as soon as the cue is presented.

In the present experiment, it is important to ensure that task-set reconfiguration is being measured by the task switching paradigm. This is the component of switch costs which likely reflects attentional control, and is thus the component that would be expected to show a relationship with WMC. Given this, the present experiment will closely follow the recipe for measuring task-set reconfiguration as outlined by Monsell and Mizon (2006).

4.1.1.1 Do cue switch costs and task switch costs reflect different processes?

Since the first examination of cue switch costs, studies using the 2:1 cue to task mapping paradigm have consistently found that such cue switch costs exist, supporting the idea that cue encoding benefits do play a role in generating switch costs. However, such research has also shown that true task switch costs still account for a large portion of the slowed response time on task switch trials (Altmann, 2006; Arrington, Logan, & Schneider, 2007; Jost et al., 2013; Jost et al., 2008; Mayr, 2010; Monsell & Mizon, 2006; Schneider & Logan, 2011). The question is whether this is a problem. If cue switching and task switching reflect the same cognitive processes, then there is no need to separate them. However, this does not appear to be the case as cue switch costs and task switch costs are dissociable both behaviourally, and at the neural level (see Jost et al., 2013 for review). Behaviourally, studies have shown that manipulations of the response-to-cue interval (Horoufchin, Philipp, & Koch, 2011) and cue-to-stimulus interval (Mayr & Kliegl, 2003; Monsell & Mizon, 2006) have different effects on task switch and cue switch costs.

At the neural level, functional magnetic resonance imaging (fMRI; De Baene & Brass, 2011) and event-related potential (ERP; Jost et al., 2008) studies, have shown that cue switch costs and task switch costs do not recruit the same network of brain regions during task performance. The fronto-parietal network that is often associated with task switching (Richter & Yeung, 2014), and which has been referred to as the cognitive control network (Cole & Schneider, 2007) is also associated with ‘true’ task switch costs (task switch versus cue switch contrast) when a 2:1 cue to task mapping paradigm is used (De Baene & Brass, 2011). What is particularly interesting though, is that cue switch costs (cue switch versus cue repeat contrast) are not related to activity in these same fronto-parietal areas. This suggests that cue switching and task switching likely reflect different cognitive processes.

The ERP effects of task switch and cue switch costs are also very different both temporally and spatially (Jost et al., 2008). Cue switching, relative to no switch trials, showed a relative negativity 300 ms after the cue was presented, with a maximum in the centrofrontal area. Such activity is likely linked to the encoding and interpretation of the cue. In contrast, task switching, as compared to cue switching showed a negativity that started much later, around 400 ms after the stimulus was presented, and it showed a topography that was very different from that shown by the cue switch contrast. It was distributed much more broadly and in both frontal and parietal electrodes. The authors argued that while their study does not make suggestions about the processes underlying the two components of switch costs, the results do suggest that task switch and cue switch costs are not indexing the same process. These findings point to the importance of using a task switching paradigm that allows for the calculation of both cue switch and task switch costs given that they likely index different cognitive processes. We will now turn to a discussion of which cognitive processes task switch costs and cue switch costs are thought to reflect.

4.1.1.2 Theoretical explanations of cue switch costs and task switch costs.

Researchers are now in agreement that both cue switch costs and 'true' task switch costs are present in the standard version of the task switching paradigm (Arrington et al., 2007; Jost et al., 2013). However, there remains a great deal of debate regarding what cue switch costs and task switch costs actually represent. Several researchers maintain that the task switching paradigm still measures task-set reconfiguration and indexes cognitive control abilities, but they differ in their thoughts about whether this is indexed by task switch or cue switch costs. Monsell and Mizon (2006) argue that 'true' task switch costs measure the endogenous act of task-set reconfiguration. Given this, 'true' task switch costs, after accounting for cue switching, should serve as an index of attentional control abilities. In contrast, they argue that cue switch costs do not reflect attentional control, but are instead due to a passive perceptual priming process. Performance benefits on cue repeat trials may be due to early detection of cue repetition which leads the participant to maintain the current task set, or it could be due to cue encoding facilitation on cue repeat trials (Monsell & Mizon, 2006). A similar argument regarding cue switch costs has been put forth by others (Arrington et al., 2007; Logan & Bundesen, 2003; Schneider & Logan, 2005).

Although Monsell and Mizon (2006) argue that task switch costs reflect endogenous attentional control and cue switch costs reflect a passive, automatic process, Mayr and Kliegl (2003) argue the opposite. They suggest that cue switch costs represent the retrieval component of task switching. When the cue is presented, it drives the retrieval of task rule information from LTM into working memory so that it is ready when the stimulus appears. ‘True’ task switch costs represent the application component, in which the task rules retrieved in the previous step are applied to the presented stimulus. The retrieval stage (cue switch costs) is thought to require the use of cognitive control processes to create a working memory representation (Grange & Houghton, 2010; Meiran, 2014), while the application stage (task switch costs) is a fairly automatic process which would not require control processes (Mayr & Kliegl, 2003). Clearly, there is some disagreement regarding which component of task switch costs reflect endogenous control processes.

In addition to these theories that espouse the idea that task switching paradigms still serve as a useful index of cognitive control, there is the compound-cue retrieval account (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Schneider & Logan, 2005). This account argues that task switching does not measure control processes in any way, regardless of whether cue switch costs or task switch costs are considered. Instead, participants do the same thing on each trial. They see the cue word, and then the stimulus, and they form them into a compound which they use as a joint retrieval cue to retrieve the relevant response from LTM. Executive control processes are not necessary for successful task performance as you do not need to switch and reconfigure your task set on each trial. Instead, the task set remains the same: create a joint retrieval cue, search memory, and respond with what you have retrieved from memory. The authors turned to repetition priming effects to explain the existence of switch costs in the literature.

Early versions of the compound-cue retrieval account argued that ‘true’ task switch costs did not exist at all (Logan & Bundesen, 2003, 2004). All switch costs could be reduced to cue switch costs. Later modifications to their model adjusted this notion and conceded to the existence of ‘true’ task switch costs (Arrington et al., 2007).

However, the authors still maintain that both cue switch and task switch costs reflect passive priming processes that do not require any endogenous acts of control. Cue switch costs result from repetition priming, which speeds cue encoding when the cue repeats (Arrington et al., 2007; Logan & Bundesen, 2003; Schneider & Logan, 2005). This is similar to the explanation of cue switch costs put forth by Monsell and Mizon (2006). ‘True’ task switch costs also result from cue encoding benefits, but these benefits come from semantic or associative priming rather than repetition priming (Arrington et al., 2007). When two cues are used for each task, participants use the cue to pull a mediator from memory. The mediator is the task name. Once the task name is retrieved, it is combined with the target to form a joint retrieval cue which is used to retrieve the correct response from memory. On a cue switch trial, the mediator (task name) repeats, and on a task switch trial, the mediator switches, which leads to longer reaction times. Cue encoding benefits from mediator repetition. According to this model, all task switching results from either repetition priming or associative priming, there is no need to consider task-set reconfiguration or cognitive control processes to explain switching costs (Arrington et al., 2007).

It is clear that while we can now all agree that both task switch costs and cue switch costs contribute to overall switching costs, agreement regarding exactly what each of these costs represent is more challenging. Each of these theories has important implications for whether we would expect to find a relationship between switch costs and WMC. We will return to these implications when the hypotheses of the present experiment are presented.

4.1.2 Strategy use in task switching paradigms.

The compound-cue retrieval account of task switching is quite concerning for researchers who use the task switching paradigm as a measure of endogenous cognitive control. The compound-cue retrieval account argues that participants use cue-based memory retrieval processes to complete the switching task (Logan & Schneider, 2010). This involves learning the cue-stimulus-response (CSR) combinations (e.g., magnitude + 7 = right key) that are being used in the experiment across a series of practice trials. When a cue and stimulus are later presented, the participant can search their memory for the appropriate response based on their learning. This is certainly possible, especially when a small number of stimuli are used across the experiment. Others have agreed that associative learning processes likely play an important role in task switching (Abrahamse, Braem, Notebaert, & Verguts, 2016; Braem & Egner, 2018). Given this, it is important that we consider the types of strategies that participants are using when they are completing the switching task. Are they using a CSR learning strategy as suggested by the compound-cue retrieval account? Or are they approaching the task using a task set strategy which is more hierarchical in nature? Such a strategy would involve viewing the cue, selecting a classification rule based on that cue (e.g., cue = magnitude, must indicate whether stimulus is less than or greater than 5), and then selecting a response based on the stimulus (e.g., the stimulus is 7, must push right key based on the cue information provided). This is the type of strategy that has traditionally been assumed to have been used on the task switching paradigm.

To investigate whether participants were using the CSR strategy rather than the task set strategy, one study conducted a series of experiments with varied instructions (Forrest, Monsell, & McLaren, 2014). Some participants were instructed to complete the task using a CSR strategy, and were given all of the possible CSR’s and instructed to learn them. While the other group of participants were given standard task switching instructions. Across three experiments, participants in the CSR group and those in the standard switching group showed distinct patterns of results. Participants in the CSR group showed small switch costs that showed no impact of preparation, and they showed large congruency effects. In contrast, those in the task set strategy group showed results that were more consistent with the task switching literature. They showed large switch costs that were reduced with preparation time and small congruency effects. Overall, this shows that a CSR strategy is certainly possible, however it elicits a different pattern of results that are not in line with what is usually found in the literature. In contrast, those given standard task switching instructions performed as expected, suggesting that when standard instructions are given, a CSR strategy is not implemented.

This study has highlighted the importance of considering strategy use when using the task switching paradigm (Forrest et al., 2014). It does not look like participants are approaching the switching task using a compound-cue retrieval strategy as suggested by Logan and colleagues (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010). However, one of the most interesting pieces of information to come out of their experiment was at the debriefing stage (Forrest et al., 2014). After participants had completed the experiment, they were interviewed about their strategy use to ensure that the strategy manipulations were successful. Across Experiments 2 and 3, they found that 14/46 participants in the task set strategy group had actually used some CSR strategy alongside the task set hierarchical approach. In a standard task switching experiment with a small number of stimuli, a small percentage of participants may be utilizing a CSR strategy to some degree. Given this, it is important to enquire about strategy on the switching task. To address this, the present study asked participants about their strategy use after they have completed the task.

4.1.3 Aims and hypotheses.

The main aim of this experiment is to explore whether task switch costs and WMC are related once the confounding effects of cue switch costs have been accounted for. A secondary aim is to examine whether a relationship exists between cue switch costs and WMC.

With regard to ‘true’ task switch costs, the first hypothesis predicts a significant relationship between WMC and task switch costs. It is thought that ‘true’ task switch costs reflect endogenous task-set reconfiguration (Monsell, 2003; Monsell & Mizon, 2006; Rogers & Monsell, 1995). In the standard single cue version of the switching paradigm, such costs are confounded by cue switching. If we control for the effects of cue switch costs and isolate the component of task switching which reflects executive attentional control, it is expected that that switch costs will be related to WMC, which also indexes executive attentional control. Given that the present experiment closely followed the recipe for measuring task-set reconfiguration, it is expected that this attentional control component will be isolated (Monsell & Mizon, 2006). However, it should be noted that other theories of task switch costs lead to different predictions. The compound-cue retrieval account of task switching predicts no relationship between WMC and task switching as this theory maintains that no executive attentional control is required to perform the switching task (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Schneider & Logan, 2005). It has also been argued that ‘true’ task switch costs reflect the more automatic process of applying task rules to a stimulus once it has been presented (Mayr & Kliegl, 2003). Such a theory would not predict a relationship between task switch costs and WMC.

With regard to cue switching, the second hypothesis predicts no relationship between WMC and cue switch costs. Cue switch costs are thought to reflect a passive perceptual priming process which creates benefits for cue encoding on task repeat trials (Arrington et al., 2007; Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Monsell & Mizon, 2006; Schneider & Logan, 2005). Cue switch costs do not reflect any kind of executive attentional control process, and thus it is unlikely that they will be related to WMC. However, it should be noted that others have suggested that cue switch costs may actually index cognitive control mechanisms (Grange & Houghton, 2010; Meiran, 2014), perhaps reflecting a task set retrieval stage in which task rules are retrieved from LTM and made into a working memory representation (Grange & Houghton, 2010; Mayr & Kliegl, 2003). If this is the case, and cue switch costs do index attentional control processes, this theory would predict a relationship between WMC and cue switch costs. The present experiment hopes to shed some light on the theoretical debates around task switch and cue switch costs.

As recommended by the recipe for measuring task-set reconfiguration, timing parameters were also be manipulated in this experiment. The cue-to-stimulus interval (CSI) and response-to-cue interval (RCI) were manipulated while keeping the response-to-stimulus interval (RSI) constant. The strongest relationship between WMC and task switching is expected when the CSI is kept short (RCI-CSI: 1000–100 ms). Under such conditions, participants will be taxed as they have no time to prepare for the upcoming stimulus after the cue has been presented. Previous research that found a relationship between WMC and task switching only found this relationship in the most challenging timing condition (Butler et al., 2011). We know that the relationship between WMC and attentional control tasks generally only emerges under particularly taxing conditions (Kane & Engle, 2003; Poole & Kane, 2009; Robison et al., 2018). The relationship between WMC and task switching may be less robust in the less challenging timing condition (RCI - CSI: 100–1000 ms) in which participants have ample time to prepare for the upcoming stimulus.

Finally, strategy use was also examined. It is expected that most participants will report using the task set strategy. It is possible that some participants may report using the CSR strategy, as has been shown in previous studies (Forrest et al., 2014). However, this experiment used a large stimulus set, which may make the CSR strategy more challenging, discouraging participants from adopting it.

4.2 Method

4.2.1 Pre-registration.

This experiment was pre-registered at the Open Science Framework (OSF) and the pre-registration can be accessed at the following link: https://osf.io/62vjh/?view_only=d328a26b364d4c68aee32fdc316dc7d0. This experiment has the same power requirements as the previous experiments. However, sample size was increased to detect the smallest effect size reported in previous research. Butler et al. (2011) used 94 participants to explore the relationship between WMC and task switching and found a significant relationship with an effect size of .26. An a priori sample size analysis using G*Power 3 with conducted. A sample size of 97 would be necessary to detect an effect size of .25 for the correlational analysis with an acceptable error rate (alpha = .05, beta = .20). Based on this, and the sample size used by Butler et al. (2011), the aim was to collect data from 100 participants for the present study.

4.2.2 Participants.

One hundred and three participants were recruited from the Manawatu campus of Massey University (68 female; age: *M* = 21.10; *SD* = 3.37, maximum age = 30). One participant was excluded from the analysis for failing to achieve 85% accuracy on the switching task, leaving 102 participants for the analyses. All participants reported normal colour vision.

4.2.3 Apparatus and stimuli.

The apparatus and stimuli were identical to those used in Experiment 1 (See Chapter 2 for details). All three of the WMC tasks were administered using E-Prime Version 2.0 software (Psychology Software Tools Inc, 2012). The E-Prime programs were downloaded from the Engle Attention and Working Memory Lab, available at http://englelab.gatech.edu/tasks.html (Foster et al., 2015). The 2:1 cue to task mapping paradigm was programmed in python and administered using PsychoPy software (Peirce, 2007).

4.2.4 Materials and procedure.

Each participant completed the three WMC tasks in the following order: operation span (OSpan), symmetry span (SymSpan), rotation span (RotSpan). This order matches what has been adopted in previous studies (Foster et al., 2015). Following the WMC tasks, participants completed the switching task. All participants were tested individually. The entire session lasted approximately 90 minutes. Order was not counterbalanced, as is standard in individual differences research.

4.2.4.1 Working memory capacity tasks.

To measure WMC, three established complex span tasks were used to create a composite score of the WMC construct (Foster et al., 2015). As discussed in Chapter 3, a limitation of the previous experiments completed in this thesis was that only a single WMC measure was used to index WMC. It has been recommended that WMC be measured using multiple tasks rather than just a single indicator to reduce the impact of task-related variance (Draheim et al., 2018; Foster et al., 2015). To address this, participants completed the OSpan, SymSpan, and RotSpan tasks. These tasks were chosen as they have been widely used in the literature (Draheim et al., 2018; Felez-Nobrega, Foster, Puig-Ribera, Draheim, & Hillman, 2018; Foster et al., 2015). Shortened versions of these tasks were used to reduce administration time. Administering shortened versions of the complex span tasks does not substantially decrease their reliability or predictive validity or their ability to predict fluid intelligence (Foster et al., 2015). Based on previous research, participants completed one block of the OSpan, two blocks of the SymSpan, and two blocks of the RotSpan (Foster et al., 2015). This is presented as model 18 in Foster et al.'s (2015) overview of the reliability of shortened complex span tasks. It was chosen as it accounts for 96.5% of the predicted fluid intelligence variance, and most subjects can complete these tasks in less than 48 minutes. This meets the minimum recommended cut-off point which suggests choosing a set of WMC tasks that account for at least 90% of the full model variance when predicting the fluid intelligence factor (Foster et al., 2015).

The three complex span tasks all share the same structure. They each include a processing (distractor task) and storage (memory task) component. In each task, participants were given a series of stimuli to remember, and in between each to-be-remembered item a distractor task needed to be performed. Automated versions of the tasks were administered following the procedures of Unsworth et al. (2005). Each task began with three practice blocks. For the first practice block, participants completed the memory task without the presence of distractors. On the second practice block, participants completed the distractor task without having to remember anything. Participants were timed while completing the distractor tasks and this was then used to create a time limit for the experimental trials. During the experimental trials, participants had to respond within 2.5 standard deviations of their mean response time from the practice session. It is important to have a limit on response times on the distractor trials during the experiment as it reduces the participant’s ability to rehearse the to-be-remembered items when they are supposed to be performing the distractor task. Finally, in the third practice block, participants practiced the experimental task which involved performing the memory and distractor tasks simultaneously. Feedback was provided following each practice trial.

Operation span task (OSpan). The OSpan task used for this experiment is described thoroughly in Chapter 2. In contrast to Experiments 1 and 2, only one block of this task was completed. The size of each set ranged from 3-7 operation-letter pairs, with one of each sequence length presented in a random order within the block for a total score out of 25.

Symmetry span task (SymSpan). The distractor task for the SymSpan involved judging whether a shape was symmetrical along the vertical axis, and the memory task involved remembering the location of red squares which were presented in a 4x4 grid (Foster et al., 2015; Kane et al., 2004). Each trial included a symmetry judgement and the presentation of a red square. First, the symmetry judgement task was displayed. This task consisted of an 8x8 grid, with some squares coloured black. Participants had to decide if the grid was symmetrical along the vertical axis. The participant would click the mouse button when they were ready to make a decision and would then respond with a mouse click of yes if it was symmetrical, and no if it was not. A 4x4 grid was then presented with one of the squares coloured red. The location of the red square needed to be remembered. After a series of such trials, a 4x4 grid was displayed and participants needed to select the locations of the red squares they recalled, and they had to do so in the correct order. Feedback was then presented for 2000 ms indicating how many red squares were correctly recalled before the next set of trials began. The size of each set ranged from 2-5 symmetry-location pairs, with one of each of the sequence lengths presented in a random order within each block. Two blocks of this task were completed for a total score out of 28.

Rotation span task (RotSpan). For the RotSpan, the distractor task involved judging whether a rotated letter was presented the correct way, or was a mirror image of the letter, and the memory task involved remembering the size and location of arrows radiating from the centre of the computer screen (Foster et al., 2015; Kane et al., 2004). Arrows could be short or long and were pointing in one of eight directions (0°, 45°, 90°, 135°, 180°, 225°, 270°, or 315°). The distractor task involved the presentation of a normal or mirror-imaged J, G, F, or R rotated in the same 8 directions noted above. Participants needed to mentally rotate the letter and click the mouse button when they were ready to make a decision. They responded with a mouse click of yes if the letter was normal, and no if the letter was a mirror image. An arrow was then presented and its size and location needed to be remembered. After a series of such trials, all 16 possible arrows were displayed and participants then selected the arrows they saw in the correct order. Feedback was then presented for 2000 ms indicating how many arrows were correctly recalled before the next set of trials began. The size of each set ranged from 2-5 rotation-arrow pairs, with one of each of the sequence lengths presented in a random order within each block. Two blocks of this task were completed for a total score out of 28.

4.2.4.2 Double cued task switching paradigm.

On each trial, participants were required to make a judgement about the colour or shape of a stimulus presented. Each trial began with the presentation of an explicit cue instructing the participant of which task to perform. Two cues were assigned to each task. When the cue “Colour” or “Hue” was presented, participants needed perform the colour task and press 1 if the stimulus was coloured and 2 if it was grey. When the cue “Shape” or “Form” was presented, they needed to perform the shape task and press 1 if the stimulus was a triangle and 2 if it was a rectangle. Stimulus-response mappings were counterbalanced across participants. The CSI was either 100 ms or 1000 ms, depending on the block, and cues remained visible until the response for that trial was given. Cues were printed in white text on a black background. The stimulus was then displayed and remained on the screen until a response was made or 2000 ms had elapsed. Responses were made with the index and middle finger of the dominant hand using the number keypad. Once a response was provided, the stimulus would disappear, and a blank screen was presented for an RCI of 100 ms or 1000 ms depending on the block. After the RCI, the cue for the next trial appeared. Participants completed eight experimental blocks consisting of 97 trials, for a total of 776 trials across the experiment. Half of the blocks had an RCI-CSI of 100-1000 ms and the other half had an RCI-CSI of 1000-100 ms, thus the RSI remained constant at 1100 ms. These timings were interleaved in a block-wise manner. Instructions and stimulus-response reminders were presented before each block.

Within each block, the frequency of the different trial types was as follows: 25% no switch (the cue and the task repeat), 50% cue switch (the cue switches, but the task repeats), and 25% task switch trials (both the cue and the task switch). See Figure 20 for a visual depiction of these trial types. The probability of a task switch was .25. The probability of a task switch given a cue switch was .33. These probabilities have been used previously to examine task-set reconfiguration in the context of the double cuing paradigm (Monsell & Mizon, 2006). It is important to control for the conditional probability of a task switch given a cue switch as previous research has shown that participants respond to this probability (Mayr, 2006). A higher probability of a task switch given a cue switch may bias participants to initiate a task switch any time the cue switches and to abandon the current task set. If this is the case, we may see reduced true switch costs and increased cue switch costs when the conditional probability of a task switch given a cue switch is high (Mayr, 2006). To mitigate this, probabilities were kept low.

Using two cues per task generates four different types of two-trial sequences (Mayr, 2006; Monsell & Mizon, 2006):

- Task Repeat: Both cue and task repeat (A-A, B-B, C-C, D-D)
- Cue Switch: Cue switches, task repeats (A-B, B-A, C-D, D-C)
- Task Switch 1: Both cue and task switch (A-C, B-D, C-B, D-A)
- Task Switch 2: Both cue and task switch (A-D, B-C, C-A, D-B)

In these sequences, A= Colour, B= Hue, C= Shape, and D= Form. In terms of specific cue-cue transitions, I used the distribution previously used by Monsell and Mizon (2006), Experiment 6. The probability of the four specific task repeat transitions was 25%, and of the four specific cue switch transitions was 50%, the probability of the task switch 1 transitions was 12.5% and of task switch 2 transitions was 12.5%. Each of the specific cue-cue transitions appeared equally within these parameters.

Participants completed 8 experimental blocks. The task sequence within each block was randomized with the constraints that the probabilities of the three trial types (task repeat, cue switch, task switch) was maintained. Within these probabilities, all four cues were equally distributed, as was congruency and response. Each of the 16 stimuli appeared an equal number of times throughout the blocks, and no stimulus was directly repeated. A novel trial sequence was generated for each participant.

Following each block of trials, participants were presented with feedback on their performance. They were presented with their mean reaction time and accuracy rate along with an overall score. Scores were calculated by applying 1 point per 10 ms of mean reaction time (RT) plus five points for any errors. Participants were encouraged to try to keep their scores as low as possible and to try to beat their previous score. In addition, they were encouraged to try and beat the current top score achieved by other participants which was printed in the laboratory testing room. Instructions encouraged participants to use any time they had available between the cue and stimulus presentation to prepare to respond to the upcoming trial. These recommendations were adopted from the recipe for measuring task-set reconfiguration created by Monsell and Mizon (2006).

Before completing the experimental blocks, participants completed two 32 trial single task practice blocks, and two 32 trial switching practice blocks. On the first practice block, they performed the colour task on all trials, so only the cues “Colour” and “Hue” were presented. The block had an RCI-CSI of 100-1000 ms. On the second block, they performed the shape task on all trials, so the only cues presented were “Shape” and “Form” with an RCI-CSI of 1000-100 ms. On the third and fourth practice blocks, all four cues were presented and participants switched between performing the shape and colour task just as in the experimental blocks with both RCI-CSI combinations represented. These practice blocks allowed participants to become familiar with the stimulus-response mappings, and to practice in each of the timing situations that would be presented in the experimental blocks. During the practice blocks, reminders of the stimulus-response mappings were available at the bottom of the screen. These reminders were removed before the experimental trials began.

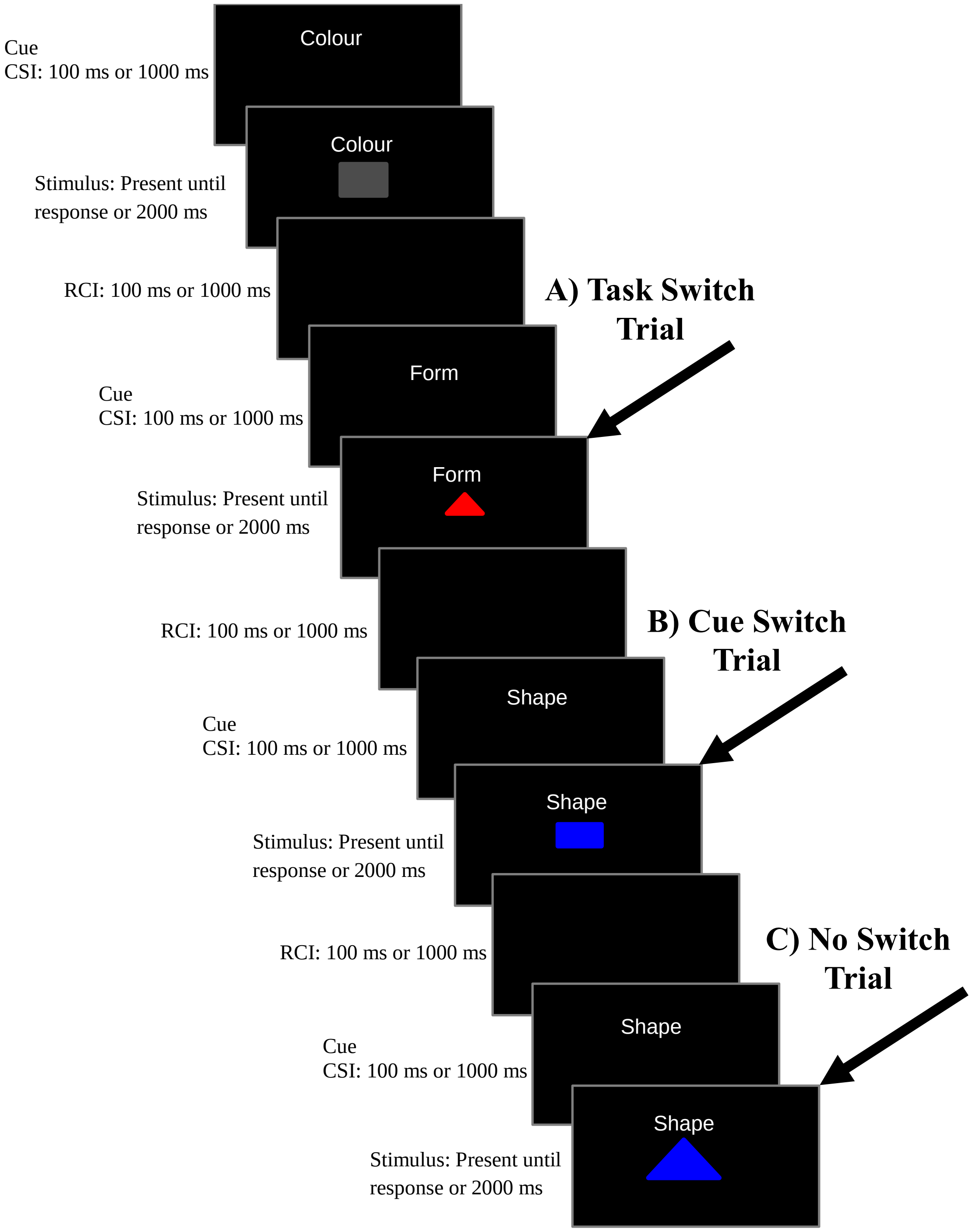


Figure 20. The trial sequence used in the 2:1 cue to task mapping paradigm. A cue was presented on each trial. Participants were instructed to read the cue and use the cue information to prepare for the upcoming stimulus. When the stimulus was presented, participants were to respond as quickly and as accurately as possible. Three trial types were presented; A) A task switch trial was one in which both the cue and the task switched from the previous trial. B) A cue switch trial was one in which the cue word switched from the previous trial, but the task to be performed remained the same. C) A no switch trial was one in which both the cue word and the task to be performed remained the same as on the previous trial. CSI: cue-to-stimulus interval; RCI: response-to-cue interval.

4.2.4.3 Assessment of strategy use.

One reason for the hypothesis that WMC and task switching should be related is that they are both posited to measure endogenous attentional control. Some research has suggested that a small subset of participants may use an associative learning strategy when completing the standard task switching paradigm which would not require the recruitment of attentional control (Forrest et al., 2014). To gather information about strategy use on the task switching paradigm, participants were asked about their strategy use at the end of the study session. This involved asking participants an open-ended question about how they approached the switching task.

4.2.5 Scoring.

4.2.5.1 Working memory capacity.

For each of the three working memory tasks, absolute and partial span scores were calculated and used to create two composite scores; a composite absolute span WMC score and a composite partial span WMC score. Absolute span scores were calculated by examining the sum of all perfectly remembered sets. Partial span scores were calculated by summing the total number of items recalled in the correct order even when the set was not remembered in its entirety. For the OSpan task, the number of letters recalled was used to calculate span scores. For the SymSpan and RotSpan tasks, the number of correctly recalled red square locations, and the number of arrows correctly recalled were used to calculate span scores, respectively. Once a WMC score was generated for each of the individual tests, scores were transformed into *z* scores and a mean *z* score was calculated, generating the two composite WMC scores. This approach has been taken in a number of previous studies using multiple complex span tasks (Gonthier, Thomassin, & Roulin, 2016; Meier et al., 2018; Miller & Unsworth, 2018; Unsworth et al., 2012). Only the composite scores were used in subsequent analyses.

Although I had pre-registered a required 80% accuracy rate across the WMC tasks, accuracy rates on each individual task had not been considered. Given that shortened versions of the complex span tasks were used, it was quite easy to fall under the 80% accuracy criterion on a single task. To prevent over-exclusion of participants, a criterion of 75% accuracy on each individual WMC task was adopted. If participants failed to achieve this criterion on a WMC task, that task was excluded from the analyses. Previous studies have used accuracy rates as low as 70% to ensure participants focus on both the primary and distractor tasks (Brydges, Gignac, & Ecker, 2018). Five participants failed to meet the accuracy criterion on the OSpan, one participant failed to meet the criterion on the SymSpan, and one participants failed to meet the criterion on the RotSpan. For these participants, the composite *z* score was calculated using the two remaining tasks. No participant achieved less than 75% accuracy on more than one WMC task.

4.2.5.2 Task switching.

Difference scores. Trials were categorized into three different trial types; task switch, cue switch, and no switch. The main dependent variable for the task switching paradigm was difference scores in the form of switch costs, as used in Experiments 1 and 2 (Chapters 2 and 3, respectively), however due to the different nature of the switching paradigm used in the present experiment, switch costs were calculated differently. Task switch costs were calculated by comparing the reaction time on task switch trials and cue switch trials (task switch costs = task switch RT – cue switch RT). This allowed for the examination of switch costs while controlling for the effects of cue switching. Cue switch costs were calculated by comparing the reaction time on cue switch trials and no switch trials (cue switch costs = cue switch RT – no switch RT). See Figure 21 for a visual depiction of these calculations. Smaller task and cue switch costs are indicative of better performance. Accuracy (ACC) task switch and cue switch costs were calculated using the percentage of correct responses for the three different trial types (ACC task switch costs = cue switch ACC – task switch ACC; ACC cue switch costs = no switch ACC – cue switch ACC). Smaller ACC task and cue switch costs are indicative of better performance. See Figure 22 for a visual depiction of these calculations.

The bin scoring method. The bin scoring method was used to combine RT and ACC information into a single score (Draheim et al., 2016; Hughes et al., 2014). See Chapter 2 for a step-by-step description of this method. There were slight variations to the standard method to accommodate the 2:1 cue to task mapping paradigm used in the present study. Separate bin scores were calculated to reflect the cost of task switching and the cost of cue switching. To achieve this, Steps 2 and 3 of the standard method described in Chapter 2 were modified. These modifications can be seen below.

Step 2. Mean reaction time was calculated for all three trial types; task switch, cue switch, and no switch. This was done on a within-subject basis.

Step 3. In the calculation of task switch bin scores, the participant’s mean cue switch RT was subtracted from their RT on each accurate task switch trial. This was done on a within-subject basis. This led to an RT difference for every task switch trial for every participant. In the calculation of cue switch bin scores, the participant’s mean no switch RT was subtracted from their RT on each accurate cue switch trial. This was also done on a within-subject basis and led to an RT difference for each cue switch trial for every participant.

Steps 1 and 4-6 remained identical to what was used in previous chapters and these steps were followed both for the calculation of cue switch bin scores and task switch bin scores. The binning and subsequent bin score calculations were done independently to get an overall cue switch bin score and an overall task switch bin score. Smaller bin scores are indicative of better performance. The binning process was carried out at each timing manipulation used in the experiment.

Intraindividual variability. The Coefficient of Variation (CoV) in reaction time was also calculated as an index of intraindividual variability (CoV = *SD*/*M*). The more conservative approach was taken to this calculation by measuring CoV from no switch trials only (Kane et al., 2016). Such an approach prevents the confounding of the experimental effects (cue switch and task switch costs) with the RT variability that I am trying to measure (Kane et al., 2016; Meier et al., 2018). See Chapter 2 for a more detailed discussion of RT CoV.

4.3 Results

In the analysis of the task switching data, the first trial from each block was excluded from all analyses. Error trials, post-error trials, and trials with RTs less than 150 ms were excluded from all reaction time analyses. Eliminating error and post-error trials led to the exclusion of 10.9% of trials from the switching task. Eliminating trials with RTs less than 150 ms led to the exclusion of 0.001% of trials.

4.3.1 Task performance.

Before addressing the main research questions, two repeated measures ANOVA’s were conducted to allow for the examination of task performance on the switching task. One ANOVA was run on RT, and another on ACC. If Sphericity was violated and the Greenhouse-Geisser Epsilon value was > .75, the Huynh-Feldt correction was applied. If the Greenhouse-Geisser Epsilon was < .75, the Greenhouse-Geisser correction was applied, as recommended (Howell, 2010).

4.3.1.1 Task switching.

A 3 (trial type: task switch, cue switch, or no switch) x 2 (timing: RCI-CSI 1000-100 ms vs RCI-CSI 100-1000 ms) repeated measures ANOVA was completed for both RT and ACC. A main effect of trial type was found for both RT, $F(1.28, 129.27) = 399.73$, $p < .001$, and ACC, $F(1.72, 173.24) = 152.54$, $p < .001$. Participants were faster on no switch trials (*M* ± *SE*; RT = 590 ms ± 10) than on cue switch (RT = 620 ms ± 11.2, $p < .001$) or task switch trials (RT = 690 ms ± 13, $p < .001$). They were also significantly faster on cue switch trials compared to task switch trials ($p < .001$). These results show clear evidence of both RT cue switch costs and RT task switch costs. Regarding accuracy, participants were significantly less accurate on task switch trials (91.0% ± 0.5) as compared to cue switch trials (95.5% ± 0.3, $p < .001$) and no switch trials (95.0% ± 0.3, $p < .001$). This finding shows clear evidence of ACC task switch costs. However, no evidence of ACC cue switch costs were found as there were no differences in accuracy between cue switch and no switch trials ($p = .14$).

A main effect of timing emerged for both RT, $F(1, 101) = 734.74$, $p < .001$, and ACC, $F(1, 101) = 128.39$, $p < .001$. Participants were faster and more accurate in the RCI-CSI 100-1000 ms condition (RT = 553 ms ± 11; ACC = 95.3% ± 0.3), which allowed for preparation, as compared to the 1000-100 ms condition (RT = 714 ms ± 12.3; ACC = 92.4% ± 0.4) which did not allow for preparation in advance of the stimulus.

There was also a significant trial type by timing interaction for both RT, *F*(1.55, 156.72) = 135.26, *p* < .001, and ACC, *F*(1.63, 164.87) = 34.67, *p* < .001. See Figures 21 and 22, respectively for a visual depiction of these interactions. For RT, significant cue switch costs and task switch costs were found under both timing manipulations (all *p* values < .001). However, on blocks when participants had no time to prepare for the upcoming trial (RCI:CSI 1000-100 ms), both task switch costs and cue switch costs were larger then when time was available for preparation prior to stimulus presentation (RCI:CSI 100-1000 ms; See Figure 21). For ACC, no significant cue switch costs were found at either timing manipulation. In contrast, significant task switch costs were found at both timing manipulations with larger switch costs when no time was available for preparation (RCI:CSI 1000-100 ms), and smaller switch costs when time was available in advance of the stimulus presentation (RCI:CSI 100-1000; See Figure 22).

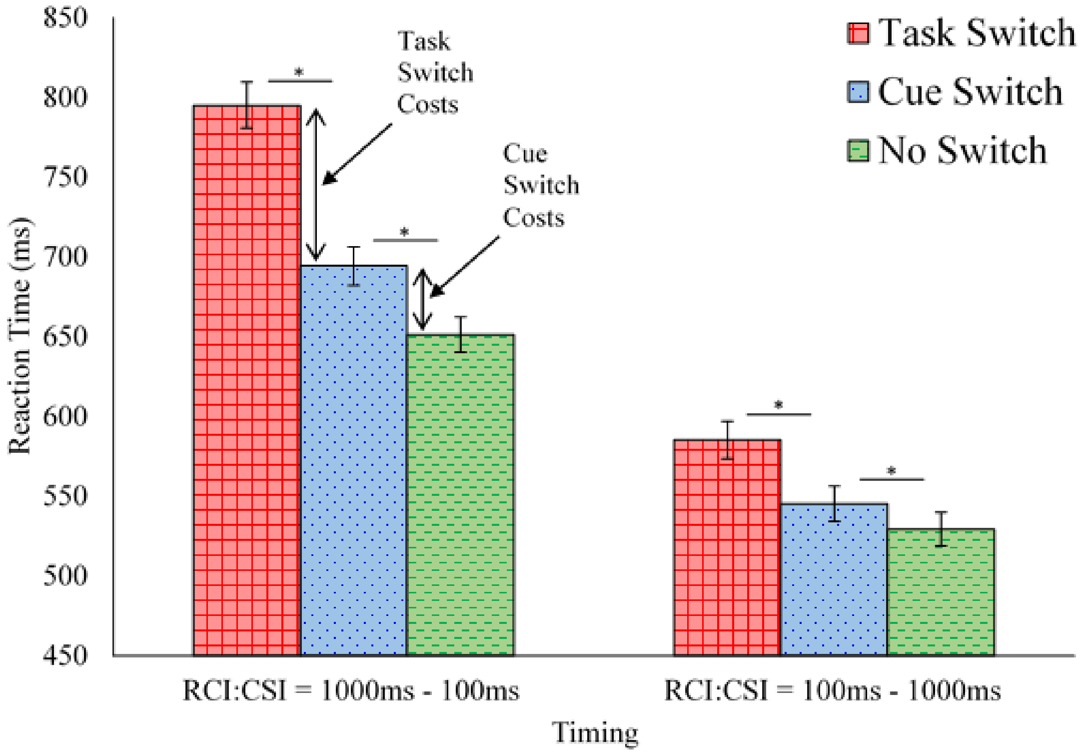


Figure 21. Mean reaction time (RT) across the different trial types (task switch, cue switch, and no switch) in each timing condition. On the left, a visual depiction of how RT task switch costs (task switch RT – cue switch RT) and cue switch costs (Cue switch RT – no switch RT) were calculated. Error bars display standard error of the mean. RCI: Response-to-cue interval; CSI: Cue-to-stimulus interval.

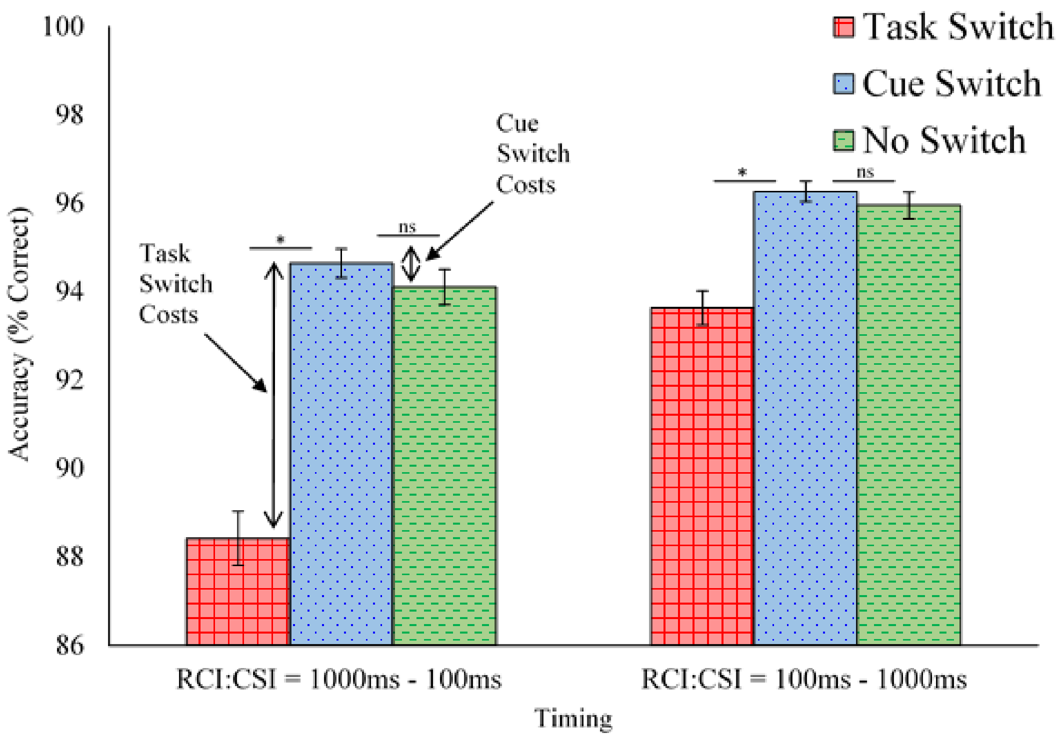


Figure 22. Mean accuracy (ACC; %) across the different trial types (task switch, cue switch, and no switch) in each timing condition. On the left, a visual depiction of how ACC task switch costs (cue switch % correct - task switch % correct) and cue switch costs (no switch % correct – cue switch % correct) were calculated. Error bars display standard error of the mean. RCI: Response-to-cue interval; CSI: Cue-to-stimulus interval.

4.3.1.2 Working memory capacity.

Absolute OSpan scores ranged from 0 to 25 (*M* = 13.40, *SD* = 6.56) and partial OSpan scores ranged from 6 to 25 (*M* = 19.08, *SD* = 4.41). Both absolute and partial SymSpan scores ranged from 2 to 28 (absolute: *M* = 14.57, *SD* = 6.90; partial: *M* = 20.24, *SD* = 5.21). Finally, absolute RotSpan scores ranged from 2 to 28 (*M* = 13.57, *SD* = 6.03) and partial scores ranged from 6 to 28 (*M* = 19.67, *SD* = 4.67). Composite *z* score variables were created for both absolute and partial span scores across the WMC tasks. The composite absolute span WMC variable was normally distributed, *K-S* (102) = 0.05, *p* = .20. However, the composite partial span WMC variable violated the assumption of normality, *K-S* (102) = 0.12, *p* = .001. Given this, the composite absolute span WMC variable was used for all analyses. Analyses were also completed using the partial span scores, and the pattern of results remained the same. The composite partial and absolute span scores were highly correlated, *r*(100) = .91, *p* < .001.

4.3.2 Exploring the relationship between working memory capacity and task switching.

As seen above, participants performed as expected on the switching task, showing both RT task switch costs and RT cue switch costs. Interestingly, while they showed ACC task switch costs, ACC cue switch costs were not found using the 2:1 cue to task mapping paradigm. We will now look at whether task switch costs were related to WMC when cue switch costs are accounted for. This will be examined first using traditional difference scores, and secondly using a combined RT/ACC score in the form of bin scores. After examining the relationship between WMC and task switch costs, we will turn our attention to whether any relationship was found between WMC and cue switch costs.

4.3.2.1 The relationship between working memory capacity and task switch costs.

To examine the first research question on whether WMC and task switch costs were related after controlling for cue switching, a series of correlational analyses were conducted. I hypothesized that a significant negative correlation would be found between WMC and task switch costs. After cue switching has been controlled for, the remaining switch costs likely reflect endogenous attentional control abilities, and thus we would expect them to be related to WMC, which also indexes attentional control. I also predicted that this relationship would be stronger when participants were especially taxed and did not have any time to prepare for the upcoming stimulus (RCI:CSI 1000-100 ms).

Table 7 displays the descriptive statistics of the RT and ACC switch costs and their correlation with WMC. For both RT and ACC switch costs, none of the correlations were statistically significant. However, for most analyses, they were in the expected direction, showing a negative relationship between WMC and task switching performance.

When the analysis was re-done with statistical outliers removed[2], the relationship between WMC and RT task switch costs in the RCI:CSI 1000-100 ms condition became statistically significant, r (98) = -.23, p = .02. See Appendix D for corresponding descriptive statistics and for a full comparison of analyses completed with and without outliers. The above analysis is the only one that altered the statistical result when outliers were removed (See Tables D-1a and D-1b). See Figure 23a for scatterplots of the relationship between WMC and RT task switch costs. For scatterplots of the relationship between WMC and ACC switch costs, see Figure D-1.

Table 7 also shows the descriptive statistics for the bin scores across each timing condition and their relationship with WMC. Bin scores are a more reliable measure of task switching performance. In line with the RT switch cost analysis with outliers removed, the bin score analysis also revealed a significant relationship between WMC and task switching, but again, only in the RCI:CSI 1000-100 ms condition. This condition was particularly taxing for participants as they had no time to prepare for the

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[2] This experiment had no extreme outliers (defined using the 3 x interquartile range (IQR) rule). However, several mild outliers were detected using the 1.5 x interquartile range rule. Analyses were re-run when these outliers were removed. The results of this re-analysis can be found in Appendix D.

upcoming stimulus following cue presentation. A relationship between WMC and bin scores was not detected overall, or in the other timing condition (RCI:CSI 100-1000 ms) which allowed time for advanced preparation. See Figure 23b for scatterplots of the relationship between WMC and bin scores. This figure highlights the consistent pattern of results seen for both RT task switch costs and bin scores in the most taxing condition of the experiment (RCI:CSI 1000-100 ms). A clear small, negative relationship can be seen in both of these scatterplots.

Table 7

Task Switch Descriptive Statistics, Reliabilities, and Correlations with Working Memory Capacity (WMC)

Measure	*M*	*SD*	Reliability	WMC *r*	*p*
Task Switch (TS) Cost RT (Switch – Repeat (ms))					
TS Cost Overall	70	34	.58	-.09	.39
TS Cost 1000-100 ms	101	51	.58	-.15	.14
TS Cost 100-1000 ms	40	34	.30	.04	.72
Task Switch Cost ACC (Repeat – Switch (%))					
TS Cost Overall	4.4	3.0	.44	-.14	.17
TS Cost 1000-100 ms	6.2	4.5	.42	-.13	.20
TS Cost 100-1000 ms	2.6	3.2	.23	-.08	.43
TS Bin Scores					
Overall	1306	140	.70	-.17	.09
Bin Score 1000-100 ms	689	95	.69	-.25*	.01
Bin Score 100-1000 ms	617	72	.54	-.01	.93

Note. Overall Cronbach’s alpha reliabilities were calculated across all 8 blocks of the experiment. In each of the timing manipulations, reliabilities were calculated across the 4 blocks of the experiment that involved that timing manipulation. All tests are 2-tailed. * $p < .05$. For ACC switch costs, the task switch cost 100-1000 ms variable violated normality, so Spearman’s rho was also calculated; $\rho(100) = -.11$, $p = .28$. RT: reaction time; ACC: accuracy.

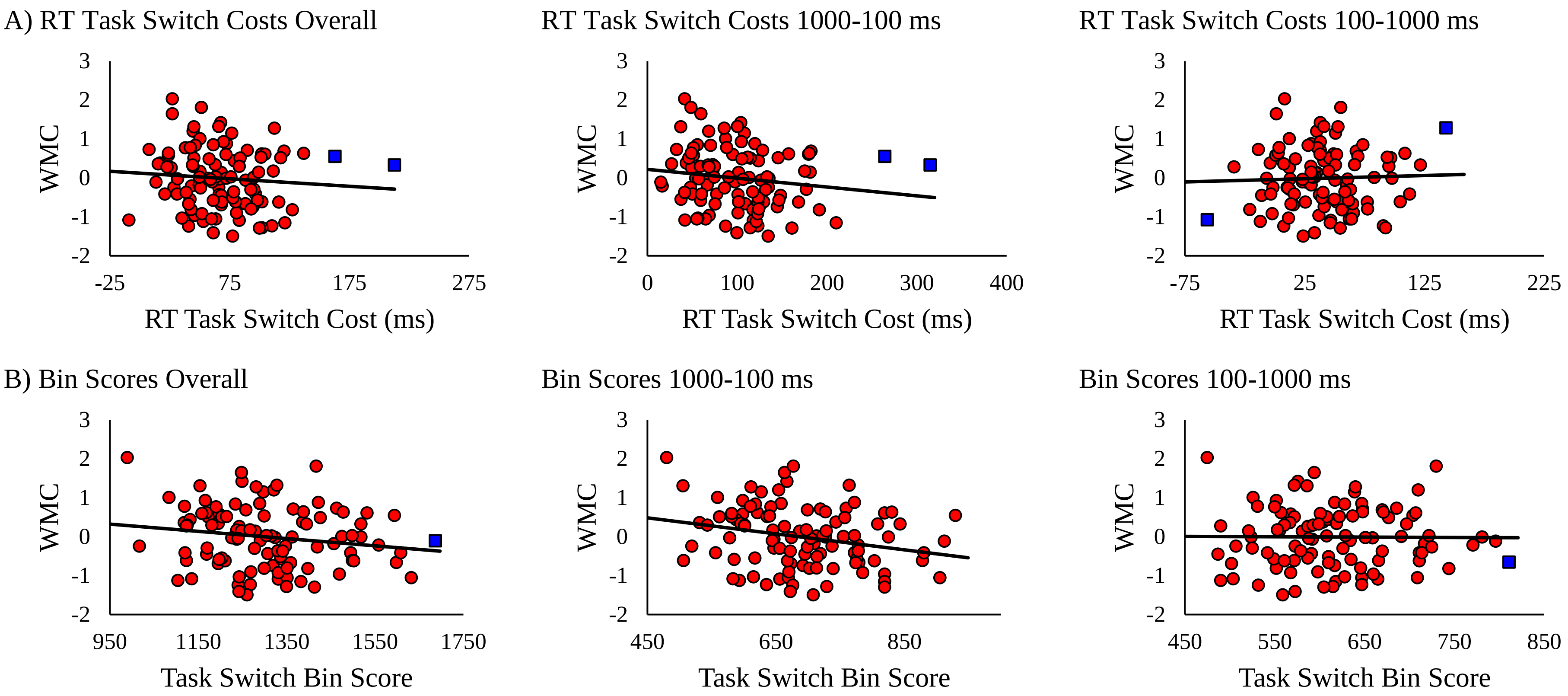

Figure 23. Scatterplots demonstrating the relationship between working memory capacity (WMC) and A) reaction time (RT) task switch costs and B) bin scores. These relationships are shown overall and across the two timing manipulations. Blue squares offer a visual depiction of mild outliers (1.5*IQR rule) which have remained in the present analysis.

4.3.2.2 The relationship between working memory capacity and cue switch costs.

To address the second research question, a series of correlational analyses were completed to examine whether WMC was related to cue switch costs. A relationship between WMC and cue switch costs was not expected as cue switch costs are thought to reflect more automatic priming processes that do not require endogenous attentional control. Given that no endogenous reconfiguration is reflected by cue switch costs, it is also unlikely that any relationship between WMC and cue switch costs will differ when time is available for preparation.

Table 8 displays the descriptive statistics of the cue switch costs and shows their relationship with WMC. No relationship between WMC and cue switch costs was found using the traditional difference scores analyses for RT or ACC (See Figure D-1 in Appendix D for scatterplots of the relationship between WMC and ACC cue switch costs). Similarly, no significant relationship between WMC and task switching was found when cue switch bin scores were examined. No support was found to suggest that cue switch costs index executive control processes. Instead, they may reflect more passive priming processes. However, it should be noted that when bin scores were examined, there was some evidence of a trend in the relationship between WMC and cue switch bin scores in the 1000-100 ms timing condition (See Table 8). While this result should not be over-interpreted, it does suggest that future research may benefit from further examining cue switch costs to determine exactly what they are indexing. Scatterplots of the relationship between WMC and RT cue switch costs as well as the relationship between WMC and cue switch bin scores can be found in Figure 24. See Tables D-2a and D-2b for a comparison of these analyses with outliers included versus excluded.

Table 8

Cue Switch Descriptive Statistics, Reliabilities, and Correlations with Working Memory Capacity (WMC)

Measure	*M*	*SD*	Reliability	WMC *r*	*p*
Cue Switch (CS) Cost RT (Switch – Repeat (ms))					
CS Cost Overall	29	24	.37	-.07	.51
CS Cost 1000-100 ms	43	34	.35	-.11	.28
CS Cost 100-1000 ms	16	29	.32	.01	.91
Cue Switch Cost ACC (Repeat – Switch (%))					
CS Cost Overall	-0.4	2.2	.18	.09	.38
CS Cost 1000-100 ms	-0.5	2.9	-.27	.06	.58
CS Cost 100-1000 ms	-0.3	2.7	.35	.08	.44
Cue Bin Scores					
Cue Bin Scores Overall	2360	193	.58	-.10	.33
Cue Bin Score 1000-100 ms	1205	122	.54	-.17	.08
Cue Bin Score 100-1000 ms	1160	132	.63	.05	.65

Note. Overall Cronbach's alpha reliabilities were calculated across all 8 blocks of the experiment. In each of the timing manipulations, reliabilities were calculated across the 4 blocks of the experiment that involved that timing manipulation. All tests are 2-tailed. * $p < .05$. For variables that violated normality, Spearman's rho was also calculated: ACC cue switch costs overall: $\rho(100) = .08$, $p = .43$; ACC cue switch costs 1000-100 ms: $\rho(100) = .08$, $p = .45$; Cue bin scores overall: $\rho(100) = -.10$, $p = .33$. RT: reaction time; ACC: accuracy.

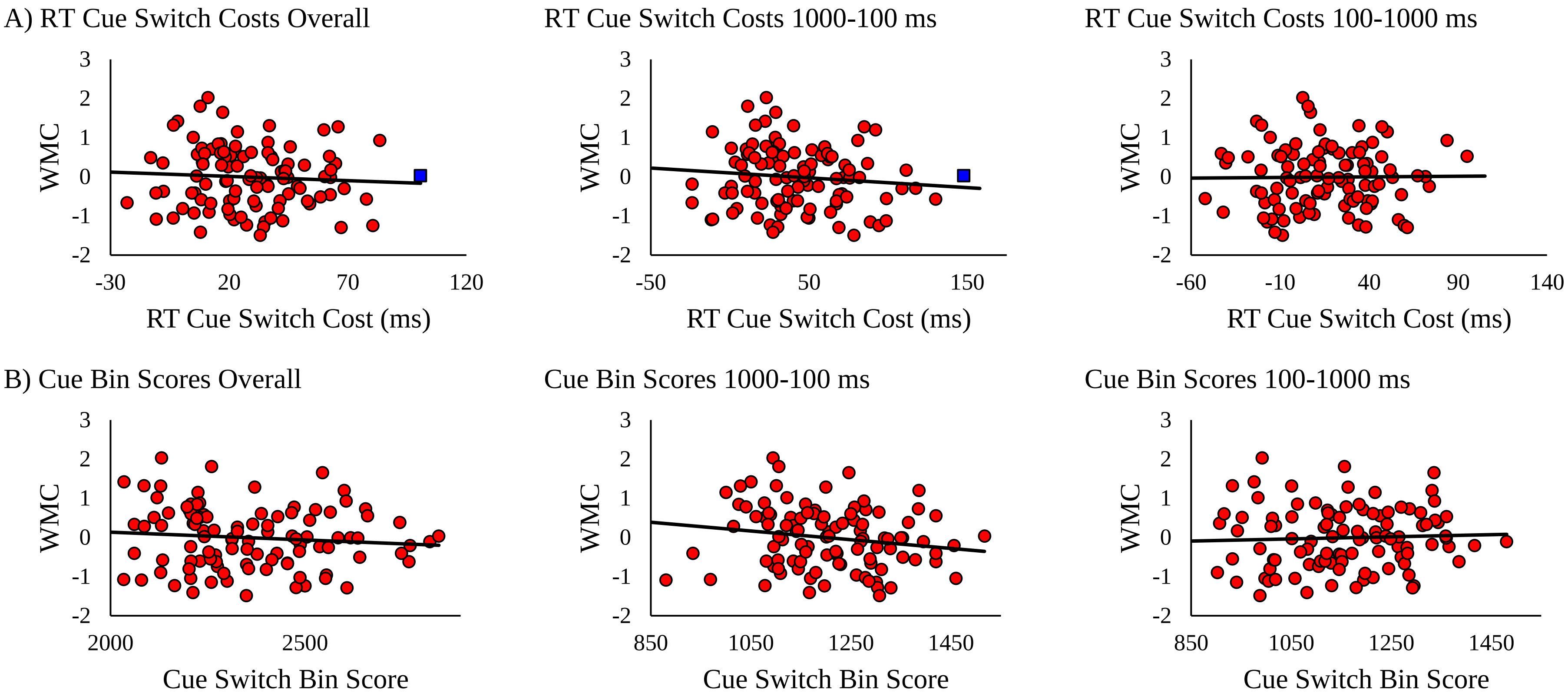

Figure 24. Scatterplots demonstrating the relationship between working memory capacity (WMC) and A) reaction time (RT) cue switch costs and B) cue bin scores. These relationships are shown overall and across the two timing manipulations. Blue squares offer a visual depiction of mild outliers (1.5*IQR rule) which have remained in the present analysis.

4.3.2.3 The coefficient of variation (CoV).

The relationship between WMC and reaction time variability on the switching task was also examined. A significant negative relationship between these variables was expected. High levels of intraindividual variability may reflect a high number of attention lapses (Kane et al., 2016). Given this, those with high RT variability would be expected to score poorly on the WMC task, which assesses attentional control. I did not find any support for this hypothesis. Similar to Experiment 2, no relationship was found between WMC and CoV overall, *r*(100) = -.03, *p* = .74, or in either of the timing manipulations, RCI:CSI 1000-100 ms: *r*(100) = -.13, *p* = .21; RCI:CSI 100-1000 ms: *r*(100) = -.07, *p* = .52. See Figure D-2 for scatterplots of the relationship between WMC and CoV overall, and in the two timing conditions.

4.3.2.4 Congruency effects.

Another aspect of the switching task that was examined was congruency costs. Based on the findings of Experiments 1 (Chapter 2) and 2 (Chapter 3), a relationship between WMC and congruency costs was not expected in a task switching paradigm with a standard level of task difficulty. There was clear evidence of congruency costs in the task switching paradigm. Participants were significantly faster on congruent trials (RT: *M* = 608 ms, *SD* = 111) as compared to incongruent trials (RT: *M* = 648 ms, *SD* = 117), *t*(101) = -17.25, *p* < .001. Similarly, participants were also more accurate on congruent trials (ACC: *M* = 97.3%, *SD* = 1.9) than incongruent trials (ACC: *M* = 91.1%, *SD* = 4.4), *t*(101) = 17.92, *p* < .001. RT congruency costs were calculated as incongruent RT minus congruent RT. ACC congruency costs were calculated as congruent ACC minus incongruent ACC. To examine whether there was a relationship between WMC and these congruency costs, a correlation was run for both RT and ACC.

This analysis revealed that WMC was not related to RT congruency costs (*M* = 41 ms, *SD* = 24), *r*(100) = .01, *p* = .96 or ACC congruency costs (*M* = 6.2%, *SD* = 3.5), *ρ*(100) = -.17, *p* = .09[3]. See Figure 25 for a visual depiction of these relationships. Outlier removal did not change the pattern of these relationships, see Table D-3a and D3-b for an overview of the results with outliers removed.

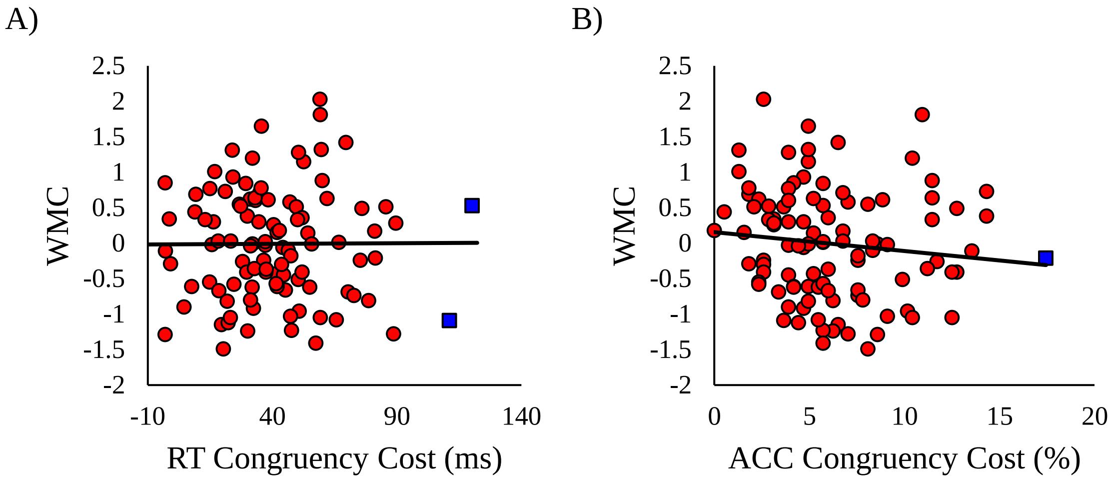

Figure 25. Scatterplots demonstrating the relationship between A) working memory capacity (WMC) and reaction time (RT) congruency costs and B) WMC and accuracy (ACC) congruency costs. Blue squares offer a visual depiction of mild outliers (1.5*IQR rule) which have remained in the present analysis. See Appendix B for analyses with outliers removed.

4.3.3 Task switching strategy use.

Following the experiment, a discussion of the type of strategy used on the switching task took place. The collection of this information was open-ended and

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[3] Spearman's Rho (ρ) was reported as ACC congruency costs violated the assumption of normality, *K-S*(102) = .12, *p* = .001.

exploratory in nature. It was expected that most participants would approach the task using a task set strategy. I did not expect many participants to report using a memory or associative learning strategy. Consistent with this prediction, no participant reported using an associative learning type of strategy. Although this can’t rule out whether such a strategy was used unconsciously, it does suggest that most people do not consciously approach the task in this way. Interestingly though, 12 participants spontaneously reported that they found that they did better on the task when they allowed their minds to go blank and just responded automatically. Such a finding suggests that perhaps some low-level associative learning processes are underway when participants are completing the switching task. The implications of this finding will be explored in the discussion section.

A number of other strategies were spontaneously reported. The most prevalent one was task cue verbalization. Fifteen participants reported verbalizing the cue words as a strategy to go as quickly as possible. Participants did notice the timing manipulations used in the study, and 21 spontaneously reported that the task was much easier when time was available for preparation between the cue and the presentation of the stimulus (e.g., RCI:CSI 100-1000 ms). Eight participants reported noticing the congruency mapping, and reported using this to assist them on congruent trials. Three participants noted that they thought there was some sort of repeating pattern among the stimuli, although each participant did receive a novel task sequence. Finally, one participant reported noticing the probability with which a switch trial would occur and they readied themselves for a switch every few trials. The implications of these self-report observations of the switching task are discussed below.

4.4 Discussion

The main aim of this experiment was to explore the relationship between WMC and task switching after controlling for the confounding effects of cue switch costs. Given the theoretical disagreement regarding what cue switch costs actually represent, a secondary goal was to examine whether cue switch costs showed any association with WMC. There was clear evidence of both reaction time task switch costs and cue switch costs. Although task switch costs were related to WMC in the most taxing timing condition, cue switch costs were not associated with WMC in any of the timing conditions in the experiment. The results of this study suggest that the elusive relationship between WMC and task switching does emerge using certain analysis techniques when cue switch costs are controlled for.

This is the first experiment to look at the relationship between task switch costs and WMC after accounting for the confounding effects of cue switch costs. In Experiment 1 (Chapter 2), the role of cues in the relationship between WMC and task switching was explored as three different task switching paradigms with different levels of instructional cues were used. However, it has been argued that even though they do not have explicit cues, the alternating runs and voluntary task switching paradigms still involve cueing processes. Participants cue themselves, using internal cues to get them ready for the upcoming task (Logan & Schneider, 2010; Mayr, 2010). Thus cue switch costs likely exist even on these paradigms that do not use explicit cues. Regardless of the switching paradigm chosen, researchers should attempt to separate out cue switch costs from task switch costs in order to index task switching abilities (Mayr, 2010). In the present experiment, I did this by using two cues for each task.

4.4.1 Examining the relationship between working memory capacity and task switch costs.

Replicating the results of previous research, substantial ‘true’ task switch costs were found once cue switch costs had been controlled for (Jost et al., 2008; Mayr, 2006; Mayr & Kliegl, 2003; Monsell & Mizon, 2006; Saeki & Saito, 2012; Schmitz & Voss, 2014). The task switch costs were also influenced by the amount of preparation time available, with larger task switch costs evident when no preparation time was available as the CSI was short. This finding replicates the results of previous research (Jost et al., 2008; Monsell & Mizon, 2006). However, it is in contrast to other studies using the 2:1 cue to task mapping paradigm which have shown no reduction in task switch costs with increases in CSI (Mayr, 2006, 2010; Mayr & Kliegl, 2003). It has been argued that these switch cost reductions with increased CSI index task-set reconfiguration (Monsell & Mizon, 2006). If this is the case, then these findings would suggest that ‘true’ task switch costs do indeed reflect endogenous control processes. The lack of reduction in task switch costs in some studies (Mayr, 2006, 2010; Mayr & Kliegl, 2003) may merely be due to task instructions. Monsell and Mizon (2006) have highlighted the idea that preparing for the task in advance is a voluntary process, that won’t come automatically to all participants and will differ based on motivation levels. If no instructions to prepare are given, participants may wait until the stimulus is presented, and therefore no reduction in task switch costs would be expected at longer CSIs. It is thus important to provide instructions that encourage participants to use the time between the cue and the stimulus to prepare themselves for the upcoming trials, as was done in the present experiment.

With regard to the relationship with WMC, I expected to find a relationship between WMC and ‘true’ task switch costs as they are thought to reflect task-set reconfiguration. Indeed, support was found for this hypothesis as ‘true’ task switch costs were related to WMC in the most taxing timing condition, when no time was available for preparation. This finding emerged from the most reliable measure of task switching, the bin score analyses which used a combined RT and ACC score. This relationship was also found in the standard RT difference score analysis when outliers were excluded. This is the first experiment to show a relationship between WMC and task switch costs after accounting for the confounding effects of cue switch costs. Such findings suggest that previous research that failed to find this relationship (Hambrick & Altmann, 2015; Kane et al., 2003; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003) may have failed because they were using task switching paradigms with only one cue per task. The cue switching confound may have masked the relationship between WMC and task switching.

The fact that we only found this relationship when little time was available to prepare for the upcoming stimulus is consistent with one of the few previous studies to find a relationship between WMC and task switching (Butler et al., 2011). Butler et al. (2011) only found this relationship in the most taxing timing manipulation in their study which did not allow time for preparation before the stimulus was presented. It seems that we are best able to measure endogenous attentional control on the task switching paradigm when participants have no time to prepare for the upcoming trial. Under such circumstances, task-set reconfiguration cannot take place in advance of the stimulus. A relationship between WMC and task switching only seems to emerge under such circumstances.

In contrast, we did not find a relationship between WMC and switch costs when participants were provided with long preparation intervals. When sufficient time is available for preparation, only the residual switch cost is measured. Residual switch costs are any costs that remain after a sufficient amount of time has been provided for preparation in advance of the stimulus (De Jong, 2000). Some have argued that residual switch costs reflect an exogenous component of task switching which cannot begin until after the stimulus is presented (Rogers & Monsell, 1995). Given this theory, it is not surprising that we have not found a correlation with WMC in this timing condition as no attentional control is thought to be required.

Another theory of residual switch costs argues that these residual costs do still index endogenous task-set reconfiguration. If this is the case, then a relationship between WMC and residual switch costs would be expected. The failure to engage hypothesis suggests that even when a sufficient amount of time is given to prepare for the upcoming trial, participants still fail to prepare on all trials (De Jong, 2000, 2001). Preparation in advance is an option, and although it may speed things up, successful task completion can still take place even if reconfiguration is postponed until stimulus presentation. Participants may just prepare in advance occasionally. When there is a long period of preparation time, switch costs reflect a mix of trials in which preparation was successful and those that were not prepared for in advance. This would explain why some switch cost is still present even at long preparation intervals.

According to the failure to engage hypothesis, we may still expect these residual switch costs to have some element of endogenous task-set reconfiguration, because people are waiting and reconfiguring on some trials after stimulus presentation. Given that residual switch costs are comprised of a mixture of switch trials in which reconfiguration took place in advance, and those in which it only took place after stimulus presentation, residual switch costs may not be a particularly reliable measure of task-set reconfiguration. This is indeed shown by the data. As seen in Table 7, across all three dependent variables (RT task switch cost, ACC task switch cost, and bin scores), task switch scores were more reliable in the RCI-CSI 1000-100 ms timing condition as compared to the 100-1000 ms timing condition. This provides support for the failure to engage hypothesis. When time was available for preparation, the reliability of the switch costs was poor, possibly because these scores comprise trials in which preparation took place mixed together with trials in which it did not. Reliability has an important impact on correlations, so the low reliability in this timing condition may explain our inability to find a robust correlation with WMC (Hedge et al., 2018).

Another thing that should be considered is the role of task difficulty. Even though it was not specifically queried, when asked about their experience with the task, 21 participants spontaneously reported that the task was easier when time was available for preparation. We know that WMC and cognitive control tasks are only related when attentional control is particularly taxed (Kane & Engle, 2003; Poole & Kane, 2009; Robison et al., 2018). It may just be that the timing condition which did not allow for task preparation was particularly difficult and that is why we are seeing the relationship emerge under those timing conditions.

Most previous research that has examined the relationship between WMC and task switching has not reported specifically on inter-trial interval lengths (Draheim et al., 2016; Kane et al., 2003; Oberauer et al., 2003), or has held the inter-trial interval constant at 500 ms (Klauer et al., 2010; Miyake et al., 2000), or held the CSI constant at 200 ms (Pettigrew & Martin, 2016). No other study using the explicitly cued task switching paradigm has manipulated the CSI to look at the impact of preparation time on the relationship with WMC. It will be important for future research examining the relationship between WMC and task switching to manipulate cue preparation time. It is likely that the switch costs that emerge from different timing scenarios will reflect different cognitive processes.

Overall, the finding of a significant relationship between WMC and ‘true’ task switch costs and the finding that task switch costs were reduced when time was available for preparation provides support for the theory that ‘true’ task switch costs reflect task-set reconfiguration (Monsell & Mizon, 2006). True task switch costs likely index endogenous attentional control.

4.4.2 Examining the relationship between working memory capacity and cue switch costs.

In addition to finding task switch costs, substantial cue switch costs were also found in the present experiment, replicating previous research using the 2:1 cue to task mapping paradigm (Jost et al., 2008; Logan & Bundesen, 2003, 2004; Mayr, 2006; Mayr & Kliegl, 2003; Monsell & Mizon, 2006; Saeki & Saito, 2012; Schmitz & Voss, 2014; Schneider & Logan, 2005). Similar to the task switch costs, cue switch costs were also influenced by preparation time. Larger cue switch costs were found when CSI was short, and smaller cue switch costs emerged when CSI was long, allowing more time for preparation. This is consistent with previous research, which has also found reductions in cue switch costs with longer CSI’s (Jost et al., 2008; Mayr, 2006, 2010; Mayr & Kliegl, 2003; Schneider & Logan, 2011). Participants may monitor whether a cue repeats, and may benefit from having the knowledge that the task will stay the same in advance of the stimulus (Monsell & Mizon, 2006). This would then speed responding even more on cue repeat trials when preparation time is available and would explain the reduction in cue switch costs with increased preparation time. Repetition priming can also benefit from preparation time.

A relationship between WMC and cue switch costs was not expected as this component of task switch costs is thought to reflect passive, perceptual priming processes rather than any kind of endogenous attentional control. The present study found no evidence to support a relationship between cue switch costs and WMC. Such findings offer support for the assertion that cue switch costs reflect passive priming rather than endogenous task-set reconfiguration (Arrington et al., 2007; Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Monsell & Mizon, 2006; Schneider & Logan, 2005).

One final aspect of cue and task switch costs worth discussing is the role of accuracy switch costs. For accuracy, ‘true’ task switch costs were found across all timing manipulations in the study. However, significant accuracy cue switch costs were not found in either timing manipulation. Such findings are consistent with previous research (Jost et al., 2008; Mayr, 2010; Mayr & Kliegl, 2003; Monsell & Mizon, 2006). Accuracy cue switch costs do not seem to exist. In contrast, for ‘true’ task switch costs, both RT and ACC switch costs are consistently found (Kiesel et al., 2010). This finding, along with the finding of a relationship with WMC for task switch costs but not cue switch costs, offers support for the idea that task switch and cue switch costs do index different cognitive mechanisms. This highlights the importance of using a switching paradigm that allows for the separation of cue switch costs and task switch costs.

4.4.3 Coefficient of variation and congruency.

4.4.3.1 Coefficient of variation.

As in Experiments 1 (Chapter 2) and 2 (Chapter 3), reaction time variability was examined as another index of cognitive performance on the switching task. This was done as it has been suggested that intraindividual variability in RT (CoV) may offer a useful index of executive attentional control abilities (Kane et al., 2016; Unsworth, 2015). A negative relationship was expected between WMC and CoV. Those with high

WMC were expected to show lower levels of CoV, indicative of stable attentional control abilities across the task, while those with low WMC were expected to show high levels of CoV, indicative of fluctuations in attentional control. Replicating the findings of Experiment 2, we failed to find any support for this hypothesis. No relationship was found between WMC and CoV in either of the timing manipulations used in this study. Although a relationship between WMC and CoV has been found with other attentional control tasks (Kane et al., 2016), this has never been examined in the context of task switching.

Our consistent failure to find any relationship between WMC and CoV suggests that perhaps this does not serve as a useful index of attentional control on the task switching paradigm. It is also possible that our calculation of CoV is not ideal. When examining attentional control tasks, one must be careful not to confound the measurement of interest, which is variability in RT, with the experimental effect of interest (cue and task switch costs). To prevent this confound, RT variability was only examined on no switch trials. This was a fairly small subset of the total trials that were completed, comprising 25% of all trials, or only 96 trials in each of the timing manipulations in the experiment. It is possible that using this small subset of trials is preventing us from adequately measuring CoV. A fix for this issue would be challenging as one would not want to add trials from the other trial types as this would create the confound that I was trying to avoid. It would be useful for future studies to examine the role of CoV in the context of task switching. Perhaps in an experiment with a greater proportion of no switch trials, allowing for more trials to go into the calculation of CoV, a more stable effect may emerge.

4.4.3.2 Congruency costs.

Similar to Experiments 1 and 2, the relationship between WMC and congruency costs was also examined. Based on the findings from Experiment 1, and the findings from the standard version of the switching task in Experiment 2, a relationship between WMC and congruency costs was not expected. The present study did not find any evidence of a relationship between WMC and congruency costs. These findings provide support for theories of congruency costs that argue that such costs reflect task set information stored in the activated portion of LTM, which is not limited in capacity (Kessler & Meiran, 2010; Liefooghe et al., 2012; Meiran & Kessler, 2008). Under normal task difficulty conditions, the experiments in this thesis have failed to find evidence of any relationship between WMC and congruency costs. Further research manipulating the level of task switching difficulty is needed to see whether the findings of Experiment 2, which found that WMC and congruency costs were only related when the switching task was difficult, can be replicated.

4.4.4 Strategy use on the task switching paradigm.

A consideration of strategy use is important when the task switching paradigm is used as strategy decisions can have an important bearing on what exactly is being indexed by task switch costs. The results of the present study are consistent with a task-set strategy rather than a CSR strategy. Participants showed consistent task switch costs that reduced with preparation time, and the magnitude of the congruency costs were more in line with a task-set strategy (Forrest et al., 2014). In terms of self-report information about the strategies used, no participant explicitly reported using a CSR strategy. This may be due to the fact that this experiment used 16 unique stimuli along with four different cues, which would require learning 64 distinct CSR mappings.

Previous research that showed that 30% of participants self-report using a CSR strategy, used only four unique stimuli and two to four cues, requiring the learning of a maximum of 16 distinct CSR mappings (Forrest et al., 2014). It should be noted however, that in the present study, 8 participants reported noticing the congruency mappings and trying to use that information to their advantage. On congruent trials, cue information did not need to be considered, participants could just press the appropriate button which corresponded to the stimulus based on memory (e.g., because red triangles were congruent, when a red triangle appeared, the correct response was always 1, regardless of the cue word). These participants only reported using such a strategy occasionally throughout the paradigm. Such findings suggest that it is likely that some memory strategies are implemented, albeit inconsistently, when completing the task switching paradigm. The use of some CSR strategies may explain why the magnitude of the relationship between WMC and task switching is smaller than we may expect.

The other interesting finding that emerged from investigating strategy use was that 12 participants reported that they performed better on the task when they allowed their minds to go blank and responded automatically without over thinking. This is a perplexing finding as one would expect that some sort of endogenous cognitive control would be necessary for successful task performance throughout the task. It would be expected that participants would be consciously implementing such control processes. This raises the question of whether some automatic, associative learning processes are involved in the task switching paradigm.

The role of associative learning in task switching has recently garnered increased interest (Abrahamse et al., 2016; Braem & Egner, 2018). Associative learning reflects an automated process that quickly generates stimulus response links that can run automatically without the need for any cognitive control (Braem & Egner, 2018;

Norman & Shallice, 1986). Traditionally, associative learning has been viewed in direct contrast with cognitive control, which is effortful, requiring concentration and attention to strategically guide behaviour (Braem & Egner, 2018; Diamond, 2013). Cognitive control is thought to be recruited when running on automatic will not suffice (Diamond, 2013). However, 12 of the participants in this study reported that they did better when they were running on automatic on this cognitive control task. It is unlikely that these 12 participants were fully using a CSR strategy as they did not show the pattern of results expected with such a strategy (Forrest et al., 2014). Instead, they showed the same pattern of results as the full sample, showing significant task switch costs that reduced with preparation time, which is thought to reflect cognitive control processes. Exactly why these participants felt like they did better when they did not concentrate and focus is unclear, and should be investigated by future research.

It is possible that associative learning is playing some sort of a role. We know that unconscious processes and contextual variables can influence performance on the switching task (Abrahamse et al., 2016; Braem & Egner, 2018; De Baene & Brass, 2014). For example, subliminally presented cues predicting the upcoming trial type can influence participant's task performance. Task switch costs are reduced when a switch trial is predicted by a subliminal cue (Farooqui & Manly, 2015). Similarly, participants can be conditioned to switch more or less depending on which trial types have been rewarded in a previous phase of an experiment (Braem, 2017). It has also been argued that not all preparatory processes are controlled by conscious strategic decisions. Participants can also use automatic processes to integrate information unconsciously across the task, which is then used to guide preparatory processes and strategic approaches (De Baene & Brass, 2014).

The learning perspective on cognitive flexibility suggests that cognitive control is grounded in associative learning processes, and the strict dichotomy that has been drawn between the two needs to be reconsidered (Braem & Egner, 2018). It is difficult to explain why the 12 participants in the present experiment reported feeling that their task performance improved when they did not focus or concentrate. However, it is possible that this has something to do with automatic learning processes guiding cognitive flexibility (Braem & Egner, 2018). Participants may be unconsciously gathering information about context, such as the probability of a task switch, and the probability of a task switch given a cue switch, and using the information that is learned to guide cognitive control behaviour. When such associative learning information is accumulated unconsciously and used to guide task performance, it may feel like the task is being performed automatically even though control processes are still involved. Automatic processes are merely guiding those control processes. It will be important for future research to continue to examine the role of associative learning in task switching. Task switching research in general should consider adding strategy use questionnaires following the switching task. Participants may not always be completing the tasks in the way that we think they are and it is important to have clear information about this.

4.4.5 Limitations.

This experiment has a variety of limitations that should be considered when interpreting the results. In an attempt to account for the limitations of the WMC task used in Chapters 2 and 3, the present experiment used three different WMC tasks and created a composite score across performance on those tasks. This helped to ensure that the WMC scores better reflected the construct of WMC, rather than task specific variance (Foster et al., 2015). However, there are still limitations with regard to the

WMC task. The primary limitation is the difficulty level of these tasks. It has been shown that the RotSpan, SymSpan, and OSpan all show fairly low levels of task difficulty and are best suited for discriminating among low ability subjects. However, they are not ideal for discriminating high ability subjects such as those whose ability levels are higher than .5 *SD*s above the mean (Draheim et al., 2018). When the standard set size used on these tasks is increased by two, the tasks become more difficult and are much better at discriminating high ability subjects. The authors argued that if multiple tasks are used to measure the WMC construct, it is not as important to include larger set sizes (Draheim et al., 2018), however it seems that the present study would have benefitted from doing so. This experiment used a high ability sample, comprised of undergraduate university students. In the present sample, one participant scored perfectly on all three of the WMC tasks, and two others garnered perfect scores on two of the tasks. Given this, there are likely some ceiling effects on the WMC tasks. Using larger set sizes likely would have allowed for better discrimination amongst the high ability participants. Future research should consider using multiple WMC tasks as well as larger set sizes when WMC is being tested in high ability populations such as undergraduate university students.

Another important limitation of this experiment is the way in which strategy use was measured. To the best of my knowledge, there are no specific strategy use questionnaires designed for task switching paradigms. Given this, strategy use was measured in a fairly open-ended way. Most of the strategy use information that was collected was spontaneous reports. Participants were asked about what kind of strategy they used on the switching task, and they were then asked directly if they used any memory strategies. Although 12 participants reported that they did better on the task when they were performing it automatically, and 21 reported that the task was easier when preparation time was available, we cannot be sure whether the other participants would agree. It is possible that all participants found the blocks with preparation time available easier than those without preparation time. It is also possible that a large proportion of participants found the task easier when they did not focus. However, because this was not specifically enquired about, we cannot be sure. They may have approached the task in a particular way, but because they were not directly asked about it, they may not have thought to report it. It will be important for future research to establish which questions are important to ask on a strategy use questionnaire in the context of task switching. The results of this experiment offer some starting points for such a questionnaire, but more extensive research in this area would be beneficial. The establishment of a standardized task switching strategy questionnaire would be of great use to the field.

Finally, another potential limitation of this is the choice of task switching stimuli. Although 16 unique stimuli were used in the present study, they varied along only two dimensions that were relevant; colour, and shape. Four different colours were used, however they could be grouped together to make the decision about whether a stimulus was coloured or grey. Similarly, although four different shapes were used that differed in size, participants may have grouped these together in their mind to make a triangle/rectangle distinction, given that size was irrelevant. Despite the attempt to have 16 unique stimuli, participants may have grouped certain factors together to reduce the number of CSR associations. Although our data do not suggest that a CSR approach was used, small numbers of stimuli can encourage associative learning strategies (Kray & Eppinger, 2006; Rogers & Monsell, 1995). To discourage the use of a CSR strategy, future research should use more diverse, and larger stimulus set sizes.

4.4.6 Summary and conclusion.

The main aim of this experiment was to determine whether a relationship between WMC and task switching would emerge once the confounding effects of cue switch costs were controlled for. Evidence for this was found, as a small, significant relationship was found between task switch costs and WMC when participants had no time to prepare for the upcoming stimulus. No relationship was found between WMC and cue switch costs. These results provide support for theories which suggest that true task switch costs offer an index of endogenous attentional control abilities and cue switch costs merely measure perceptual priming effects. Although support for a relationship between WMC and task switch costs was found, the magnitude of that relationship was small. A larger relationship would be expected if both of these tasks are measuring the same construct; attentional control. Chapter 5 well seek to explore why the relationship between these executive control tasks is not as robust as expected.

Chapter 5 – General Discussion

5.1 Exploring the Relationship between Working Memory Capacity and Task Switching

We are constantly recruiting executive functions (EF) in our daily lives. We use EF any time we conduct effortful, attentionally demanding activities, such as planning for a future event, dealing with a novel problem, or staying focussed on the task at hand; as you have been required to do while reading this thesis (Blair, 2017; Chan, Shum, Toulopoulou, & Chen, 2008; Diamond, 2013; Knapp & Morton, 2013, 2017; Logue & Gould, 2014). Given their importance in our everyday lives, it is imperative that we understand the cognitive processes that contribute to EF. Two such processes are working memory and task switching (Blair, 2017; Diamond, 2013; Diamond & Ling, 2016; Miyake & Friedman, 2012). Despite the fact that task switching and working memory capacity (WMC) are thought to contribute to EF, and have been purported to measure similar underlying constructs (Engle, 2002; Kane, Conway, et al., 2007), most research has failed to find a relationship between performance on these tasks (Hambrick & Altmann, 2015; Kane et al., 2003; Kane, Conway, et al., 2007; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003). The primary aim of the present thesis was to explore the relationship between these two constructs in more depth in an attempt to shed some light on the disconnect between the empirical findings and theoretical predictions. This chapter will begin with a summary of the major findings of this thesis, followed by a discussion of the implications of these findings and will conclude with a discussion of recommendations for future research.

5.1.1 Experiment 1.

Experiment 1 (Chapter 2) sought to explore the relationship between WMC and task switching across a variety of switching paradigms. Consistent with previous research, the planned analyses for this Experiment failed to find a relationship between WMC and task switching regardless of the paradigm used (Hambrick & Altmann, 2015; Kane et al., 2003; Kane, Conway, et al., 2007; Klauer et al., 2010; Miyake et al., 2000; Oberauer et al., 2003). See Table 9 for a summary of the main findings.

Although none of the hypotheses for Experiment 1 were supported by the pre-registered analyses, some interesting findings emerged from exploratory analyses. Participants with low WMC showed a pattern of results that largely mapped onto the hypotheses. In low WMC participants, WMC was related to task switching across all three paradigms used in the experiment. This relationship was most likely to emerge under the most taxing timing conditions across the switching paradigms, which fits with the results of one of the few previous studies to also find a relationship between WMC and switching (Butler et al., 2011). Also consistent with the hypotheses and previous research, the relationship tended to be larger when bin scores were used to score the switching data (Draheim et al., 2016). These scores also showed higher reliability. In contrast, the high WMC subgroup did not show this same pattern of results. In this subgroup, reaction time (RT) switch costs were not related to WMC in any of the paradigms or across any of the timing manipulations. This interesting pattern of results, with the hypotheses supported only in low WMC participants raised the possibility that previous research may have failed to find a relationship between WMC and task switching because they had not examined low and high WMC participants independently.

Table 9

Overview of the Main Research Questions, Hypotheses and Results from Experiment 1

Research Question	Hypothesis	Results	Exploratory Results
1) Will the relationship between WMC and task switching change depending on the amount of environmental support available?	1) A relationship between WMC and switch costs was expected. This relationship was expected to vary in magnitude depending on the amount of environmental support available.	1) RT switch costs were not related to WMC in any of the task switching paradigms. No support for the hypothesis.	1a) Low WMC – RT switch costs were related to WMC in all three of the task switching paradigms, supporting the first hypothesis. The magnitude of the relationship was similar across the three paradigms, suggesting no impact of environmental support. 1b) High WMC – RT switch costs were not related to WMC in any of the task switching paradigms. No support for the hypothesis.
2) Do specific timing parameters used in the switching task have an impact on the relationship between WMC and task switching?	2) Expected the relationship to be strongest when time pressure was highest.	2) RT switch costs were not related to WMC in any of the timing manipulations. No support for the hypothesis.	2a) Low WMC – RT switch costs were related to WMC in the explicitly cued paradigm in the RCI-CSI 100-100 ms and 100-1000 ms conditions. RT switch costs were related to WMC in the AR and VTS paradigms in the 100 ms timing condition. These findings largely support the hypothesis. 2b) High WMC – RT switch costs were not related to WMC in any of the timing manipulations. No support for the hypothesis.
3) Will a relationship between WMC and task switching emerge when a combined RT and ACC measure is used rather than traditional difference scores?	3) Expected to find a relationship between WMC and a combined task switching RT/ACC score (bin score), even if such a relationship does not exist using standard analysis techniques.	3) WMC was not related to task switching when bin scores were used. No support for the hypothesis.	3a) Low WMC – A significant relationship between WMC and bin scores was found for the explicitly cued and AR paradigms across all timing conditions. The magnitude of this relationship was slightly larger than when difference scores were examined. These findings support the hypothesis. 3b) High WMC – No relationship between WMC and bin scores in explicitly cued switching paradigm. Significant relationship between WMC and bin scores in the AR paradigm in the 100 ms timing condition.

Note. The exploratory results are from non-pre-registered analyses examining the relationship between working memory capacity (WMC) and task switching separately for low and high WMC participants. Although no specific hypotheses were made for low vs high WMC participants, the findings were compared to the hypotheses made for the full sample. RT: reaction time; AR: alternating runs; VTS: voluntary task switching paradigm; RCI: response-to-cue interval; CSI: cue-to-stimulus interval.

5.1.2 Experiment 2.

Experiment 2 (Chapter 3) set out to replicate this interesting pattern of results in a larger sample. In addition to serving as a replication, Experiment 2 was designed to examine the impact of task difficulty on the relationship between WMC and task switching. A summary of the results of Experiment 2 can be found in Table 10. This experiment failed to replicate the results of Experiment 1. Such findings in a larger sample suggest that the results of Experiment 1 are likely to be spurious results due to the low sample size. Experiment 2 also failed to find any effect of task difficulty on the relationship between WMC and task switching. After Experiments 1 and 2, it can be concluded that neither the experimental paradigm chosen, nor the task difficulty of the paradigm can explain why WMC and task switching are not related despite theoretical predictions that they should be.

Table 10

Overview of the Research Questions, Hypotheses and Results from Experiment 2

Research Question	Hypothesis	Results
1) Can the exploratory analyses from Experiment 1 (Chapter 2) be replicated in a larger sample?	1) It was hypothesized that the Experiment 1 results would be replicated. A relationship between WMC and task switching should only emerge in low WMC participants.	1) RT switch costs, ACC switch costs, and bin scores did not correlate with WMC in either high or low WMC participants. No support for the hypothesis.
2) Does the difficulty of the switching task have an impact on the relationship between WMC and task switching?	2) It was hypothesized that when task difficulty was increased, a significant relationship would be found between WMC and task switching in the entire sample.	2) In the difficult task condition, a significant negative relationship was not found between WMC and switch costs in the full sample or in low WMC or high WMC subgroup analyses. RT switch costs actually showed a positive correlation with WMC. No support for the hypothesis.
3) Do mind wandering rates during task switching differ for low and high WMC participants?	3) It was hypothesized that under low load, higher mind wandering rates would be found in high WMC participants. Under high load, higher mind wandering rates would be found in low WMC participants.	3) WMC did not have a significant impact on mind wandering during the switching task and this did not differ depending on task difficulty. No support for the hypothesis.

Note. WMC: working memory capacity; RT: reaction time: ACC: accuracy.

5.1.3 Experiment 3.

The next step in exploring the relationship between WMC and task switching was to break down the experimental design used to study task switching to see whether some aspect of that task design was leading to the null results. Experiment 3 (Chapter 4) was designed to control for the effects of cue switch costs which had been confounding the previous attempts to examine the relationship between WMC and task switching. A 2:1 cue to task mapping paradigm was used to allow for the separation of task switch and cue switch costs. It seemed possible that previous research may have failed to find a relationship between WMC and task switching due to the confounding effects of cue switch costs. This was the first experiment to examine the relationship between WMC and task switching after controlling for the role of cue switching. See Table 11 for an overview of the findings from Experiment 3. As expected, once cue switch costs were controlled for, a relationship between WMC and 'true' task switch costs was found in the most taxing timing condition. In contrast, no relationship between WMC and cue switch costs were found.

Table 11

Overview of the Research Questions, Hypotheses and Results from Experiment 3

Research Question	Hypothesis	Results
1) Is there a relationship between WMC and 'true' task switch costs after the effects of cue switching have been controlled for?	1) It was hypothesized that a significant negative correlation between WMC and 'true' task switch costs would be found.	1) Both RT switch costs and bin scores showed evidence of a relationship between WMC and 'true' task switch costs. Hypothesis was supported.
2) Is there a relationship between WMC and cue switch costs?	2) It was hypothesized that there would not be a relationship between WMC and cue switch costs.	2) No evidence of a relationship between WMC and cue switch costs was found.
3) Do specific timing parameters used in the switching task have an impact on the relationship between WMC and task switch costs?	3) It was expected that the relationship between WMC and 'true' task switch costs would be more robust under the most taxing timing condition, when no time was available to prepare for the upcoming trial.	3) For both RT switch costs and bin scores, a relationship between WMC and 'true' task switch costs was found only in the most taxing timing condition, in which no time was available for advanced preparation. Hypothesis was supported.

Note. WMC: working memory capacity; RT: reaction time.

5.1.4 Summary.

In this thesis, I have shown that when traditional task switching paradigms are used, the exact paradigm chosen has little impact on the relationship between WMC and task switching (Experiment 1; Chapter 2). Similarly, attempts to manipulate task difficulty by adding an additional distraction did not have an impact on the relationship between WMC and task switching (Experiment 2; Chapter 3). These findings suggest that task difficulty and paradigm choice cannot explain the failure of previous studies to find a relationship between WMC and task switching. Instead, this thesis has shown support for the assertion that previous studies may have failed to find a relationship between WMC and task switching because they failed to consider the confounding effects of cue switch costs. When cue switch costs were accounted for, a relationship between WMC and task switching was found (Experiment 3; Chapter 4).

We will now turn to a discussion of the implications of these findings. The findings of this thesis have important implications for theories of both task switching and WMC. They also have important implications for the way in which WMC and task switching are measured, especially when conducting individual differences research. Although a relationship between WMC and task switching was found when cue switch costs were controlled for, the relationship was quite small in magnitude. The relationship between WMC and task switching still remains fairly elusive. Possible reasons for this will be explored. Very specific experimental design considerations must be made in order for the relationship to be found.

5.2 Theoretical Implications

5.2.1 Implications for theories of task switching.

WMC provides an index of attentional control (Engle, 2002; Kane, Conway, et al., 2007; Meier & Kane, 2017). If task switching also indexes attentional control, then it should be related to WMC. If these constructs are not related, that presents a problem for theories of task switching that ascribe switch costs to attentional control processes (Underwood, 1975). Modern theories of task switching agree that switch costs do not reflect a single cognitive process. Instead, they reflect both priming processes, as well as cognitive control (Altmann & Gray, 2008; Meiran, 1996; Meiran et al., 2000; Monsell, 2003, 2017; Sohn & Anderson, 2001). The task-set reconfiguration view argues that the cognitive control component of switch costs involves task-set reconfiguration, which is an endogenous attentional control process. Task switch costs reflect the time taken by control operations to reconfigure the task-set when the task switches (Monsell, 2003, 2017; Rogers & Monsell, 1995). Switch costs at short cue-to-stimulus intervals (CSI) are thought to serve as a valuable index of the process of endogenous task-set reconfiguration, and thus attentional control (Monsell, 2017).

The primary analyses from Experiments 1 and 2 (Chapters 2 and 3, respectively) did not offer support for the task-set reconfiguration view of task switching. A relationship with WMC was not found. This is problematic for theories of task switching that ascribe switch costs to attentional control mechanisms (Monsell, 2003, 2017; Rogers & Monsell, 1995). Perhaps the switching task is not indexing attentional control in the way that we expect it to. The biggest challenge to this attentional control model of task switching comes from the compound-cue-retrieval account of switching (Monsell, 2017) which argues that no endogenous control processes are needed during task performance on the switching task (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Schneider & Logan, 2005). Given that the results of the first two experiments did not find support for an attentional control view of switching, Experiment 3 (Chapter 4) addressed the claims of the compound-cue-retrieval account.

The findings of Experiment 3 did find esupport for the task-set reconfiguration view of switching. When cue switch costs were controlled for, WMC was related to both RT switch costs and bin scores when the CSI was short. It is under exactly this timing condition that switch costs are thought to provide an index of endogenous control processes (Monsell, 2017). Experiment 3 also provided evidence to support the fact that cue switch costs do exist, as suggested by the compound-cue-retrieval account of switching. However, ‘true’ task switch costs remain even after cue switch costs are controlled for. The fact that ‘true’ task switch costs were related to WMC provides support for the fact that these costs index attentional control processes (Monsell, 2003, 2017; Rogers & Monsell, 1995) rather than passive priming processes (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010).

Overall, the findings of this thesis suggest that task switching paradigms can offer an index of attentional control abilities, as suggested by the task-set reconfiguration view (Monsell, 2003, 2017; Rogers & Monsell, 1995). However, they do so best under certain methodological constraints, and when cue switch costs have been controlled for. Researchers also need to keep in mind that while switch costs can index task-set reconfiguration, it is an impure index, as switch costs likely also reflect other more passive processes, such as task-set inertia (Monsell, 2017). We will return to a larger discussion of the use of the task switching paradigm as an index of attentional control when experimental design and measurement considerations are discussed.

5.2.2 Implications for theories of working memory capacity.

A number of working memory theories have emphasized the important role of attentional processes in working memory, however they differ regarding exactly how attention is important. Both the multiple components theory (Baddeley, 2003; Baddeley, 2012; Baddeley & Hitch, 1974) and the embedded processes model (Cowan, 1999, 2008) suggest that our attention can be controlled by a central executive. The embedded processes model argues that the central executive controls the focus of our attention, which is limited in capacity (Cowan, 1999, 2008), while the multiple components model suggests that the central executive is involved in a variety of attentionally demanding tasks such as focussing attention, dividing attention, and switching attention (Baddeley, 2003; Baddeley, 2012; Baddeley & Hitch, 1974). These theories suggest that attentional control is a vital component of working memory. Similarly, the executive attention theory of WMC argues that individual differences in WMC reflect individual differences in executive attentional control (Engle, 2001, 2002; Engle & Kane, 2004; Kane, Conway, et al., 2007). Such theories would predict a relationship between WMC and task switching, given that switch costs, in part, reflect endogenous attentional control processes (Monsell, 2003, 2017; Rogers & Monsell, 1995).

The main results from Experiments 1 and 2 (Chapters 2 and 3) failed to find support for these theories. Instead, little evidence of a relationship between WMC and task switching was found. These findings are more consistent with models that do not argue for a relationship between WMC and task switching (Oberauer, 2009; Oberauer et al., 2007; Vandierendonck, 2016). One model of working memory has suggested that although an important link exists between WMC and task switching, with working memory allowing for successful goal selection as well as task set maintenance, that does not imply that performance on these tasks needs to be related (Vandierendonck, 2016). The limited capacity resource needed to maintain the task set may be completely separate from the processes used to execute the switching task. However, this has not been shown empirically, and the author also noted that it was possible that such a relationship had not been found due to the standard difference score analyses used in the task switching literature (Vandierendonck, 2016). Indeed, we did find that bin scores are a more reliable way to assess task switching across the experiments conducted in this thesis.

Oberauer's model also argues against that a relationship between WMC and task switching is not necessary (Oberauer, 2009; Oberauer et al., 2007). In this model, one important component of procedural memory is the bridge. The role of the bridge is to form and hold the current task set in mind, ready for use. This model suggests that when a task switches, participants must retrieve a new task set from LTM to add to the bridge and they must remove the current task set from the bridge. Those with high WMC are good at binding information to the bridge. Given this, they would struggle to remove the current task set because it is strongly bound, but once removed they would be able to strongly bind the new task set successfully. In contrast, low WMC participants would have weaker bindings, which would be beneficial during task set removal, but the new task set would not be bound very strongly. Such a model suggests that both high and low WMC participants would struggle equally, but in different ways on the switching task. In Experiment 2, in which task difficulty was manipulated, the perplexing result of a positive correlation between task switching and WMC was found in the most challenging timing condition. Given the more challenging nature of this experiment with the additional distractor task, it is possible that high WMC participants had even more difficulty removing previous task sets from the bridge. Perhaps the weak bindings of low WMC participants were beneficial in such a situation. However, given the results of Experiment 3 (Chapter 4) it seems more likely that the previous findings are due to experimental design challenges such as isolating the component of task switch costs that reflect endogenous attentional control. This idea will be explored further below.

The results of Experiment 3 (Chapter 4) suggest that when certain methodological decisions are made in the design of the switching task, and cue switch costs are controlled for, “true” task switch costs can be measured, and likely index attentional control. Given that WMC was related to task switching performance under these conditions, it provides support for the models of working memory that stress the importance of executive attentional control (Baddeley, 2003; Baddeley, 2012; Baddeley & Hitch, 1974; Cowan, 1999, 2008; Engle, 2001, 2002; Engle & Kane, 2004; Kane, Conway, et al., 2007). Taking these results together, I would argue that the null results of the early chapters do not challenge executive attention theories of WMC, but are instead likely due to methodological issues with the switching paradigm itself. The task switching paradigm used in Experiment 3 (Chapter 4) was designed specifically to try and measure attentional control processes, and under these controlled conditions we did find a relationship between WMC and task switching.

5.3 Design and Measurement Considerations

During the course of this thesis project, a variety of issues related to design and measurement arose which deserve some discussion. This section will explore the issues encountered when using complex span tasks in an undergraduate university population. Limitations of the task switching paradigm will then be discussed, with an emphasis on the importance of making careful design considerations when using this task. The different task switch analysis techniques will be discussed, including some consideration of the impact of different techniques on the relationship between WMC and task switching. Finally, we will explore the utility of the task switching paradigm in individual differences research.

5.3.1 Measuring working memory capacity.

With regard to the measurement of WMC, one of the limitations of Experiments 1 and 2 (Chapters 2 and 3) was that only a single task was used to index WMC. One of the most widely used measures of WMC are complex span tasks, and the most widely used complex span task is the operation span task (Turner & Engle, 1989). Given its pervasive use in the literature, this task was used in both Experiments 1 and 2. However, when attempting to index the construct of WMC, it is important to use more than one task (Draheim et al., 2018; Foster et al., 2015). Otherwise, the WMC estimate will also include task specific variance. WMC scores from the first two experiments in this thesis likely also included task specific variance. A relationship between WMC and task switching was found in Experiment 3, when multiple tasks were used to calculate a composite score of WMC. This raises the possibility that these differing findings may be due to the measurement of WMC, rather than controlling for the confounding effects of cue switch costs. However, a great deal of the previous research which has found a relationship between WMC and other cognitive constructs has also used the operation span task in isolation (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Bleckley, Foster, & Engle, 2015; Brewin & Beaton, 2002; Conway et al., 2001; Furley & Memmert, 2012; Kane et al., 2001; Kane & Engle, 2003). Additionally, one of the few experiments to actually find a relationship between WMC and task switching used the operation span task alone as an index of WMC (Butler et al., 2011). Given this, I would argue that our findings are more likely due to the changes that were made to the task switching paradigm in Experiment 3.

Another limitation of the WMC tasks used across the three experiments is that they may not have been ideal for the participant population used. All three of the experiments used undergraduate university students as participants, who fall in the category of high ability. The complex span tasks used are not particularly good at discriminating amongst high ability participants (Draheim et al., 2018). Although it has been suggested that this is less of a concern when multiple tasks are used (Draheim et al., 2018), even in Experiment 3, the use of these complex span tasks appeared to be problematic. Several participants performed perfectly on the tasks, suggesting that we may have had some ceiling effects. This would have reduced the variability in the data set, which is particularly problematic when conducting correlational research. With low variability, and a restricted range of scores, it is more difficult to find a correlation with another cognitive construct (Goodwin & Leech, 2006). This may have made it more challenging to find the expected correlation between WMC and task switching, or may have led us to find a smaller correlation than the true relationship in Experiment 3. It will be important for future studies to account for these limitations by ensuring that multiple WMC tasks are used to index WMC, and to use tasks with larger set sizes to ensure that they capture the full range of WMC and appropriately distinguish amongst high ability participants. To make this simple, shortened complex span tasks with increased set sizes have recently been freely released and are accessible from the Attention and Working Memory Lab website (http://englelab.gatech.edu/taskdownloads.html).

5.3.2 Measuring task switching.

Despite being considered a gold-standard measure of cognitive control (Kane, Conway, et al., 2007), the task switching paradigm is not without its limitations. There are many variations of this paradigm (Grange & Houghton, 2014; Kiesel et al., 2010; Vandierendonck et al., 2010), and task switch costs are quite susceptible to minor methodological adjustments. Switch costs vary quite dramatically depending on switch probability (Mayr, 2006; Meiran et al., 2000; Monsell & Mizon, 2006; Schneider & Logan, 2006), the specific cues chosen (Logan & Bundesen, 2004), whether timing manipulations are made between subjects or within subject (Altmann, 2004a, 2004b), and the exact paradigm administered (Altmann, 2007; Arrington & Logan, 2005). Such variations make it difficult to establish under exactly which experimental conditions switch costs will serve as the best index of control processes. This means that researchers need to make a considerable number of decisions when designing the task switching paradigm as there is no standardized methodology. The recipe for measuring task-set reconfiguration (Monsell & Mizon, 2006) is a step in the right direction, but still leaves room for a number of methodological variations. The recipe for measuring task-set reconfiguration was not followed in Experiments 1 and 2, as cue switching was not controlled for, and different timing manipulations were used. It was only when the recipe for measuring task-set reconfiguration was used that a relationship between WMC and task switching was found.

The establishment of a standardized switching paradigm that could be used to index control processes in individual differences research would be beneficial to the field. This kind of standardized methodology has been established in the WMC field with complex span tasks which have been psychometrically validated and in which reliability has been verified (Conway et al., 2005; Foster et al., 2015; Redick et al., 2012; Unsworth et al., 2005). These WMC tasks are hosted on the Attention and Working Memory Lab website (http://englelab.gatech.edu) so that they are easily accessible, and as of 2015 they had been requested by more than 2000 researchers (Foster et al., 2015).

The creation of a standardized task-switching paradigm which will measure switch costs that index control processes is not without its challenges. As mentioned above, switch costs are influenced by numerous situational factors (Mittelstadt, Miller, & Kiesel, 2018; Vandierendonck et al., 2010). They do not serve as a ‘pure’ measure of endogenous attentional control (Monsell, 2017). Switch costs are thought to reflect both priming, as well as control processes (Meiran, 1996; Meiran et al., 2000; Monsell, 2003, 2017; Sohn & Anderson, 2001). When we use the switching paradigm, not only are we measuring our construct of interest; cognitive control, but we are also measuring processes that potentially don’t require control, such as passive carry-over from the previous task set (Monsell, 2017).

5.3.2.1 Confounds of the task switching paradigm.

The task switching paradigm is also plagued by a variety of confounds. One such confound is cue switch costs, and there is now some consensus in the literature that this is an important factor to consider (Jost et al., 2013). Experiment 3 (Chapter 4) showed that controlling for this confound was important for isolating the component of switch costs which reflect control processes. Research has also shown that part of the switch cost can be explained by other biases. Task switch costs are also confounded by stimulus repetitions, physical response repetitions, and conceptual response repetitions (Schmidt & Liefooghe, 2016). Conceptual responses refer to the actual task response being given (e.g., on the parity task, the conceptual response would either be odd or even, and on the magnitude task it would be lower than 5 or higher than 5). Conceptual response repetitions are possible on task repeat trials (e.g., odd - odd), however, conceptual responses cannot repeat on a switch trial (e.g., odd – higher than 5). Stimulus repetitions, and both physical and conceptual response repetitions all work against task switch trials, and in favour of task repeat trials, and thus may help to explain the switch cost. For example, physical response repetitions always coincide with conceptual response repetitions (e.g., press right key – press right key; odd - odd) on repeat trials, but physical response repetitions always coincide with conceptual response switches on a task switch trial (e.g., right key – right key; odd – higher than 5). Once these confounds were controlled for, one experiment found that task switch costs were reduced by 66 ms (Schmidt & Liefooghe, 2016).

It is not commonplace for task switching experiments to control for such factors, but it does look like they may have some influence on switch costs. Across all three experiments in the present thesis, direct stimulus repetitions were not allowed, however, physical response repetitions and conceptual response repetitions were not controlled for. In an idealized world, one would control for these additional factors, however such control is no easy feat. To control for the factors mentioned, the data have to be split into 10 trial types, and many trials need to be excluded from the calculation of the switch cost. In the experiment that was designed to control for each of these factors, only 34.38% of the 800 trials were used in calculating the final task switch cost (Schmidt & Liefooghe, 2016). If one is also interested in manipulating preparation time, an important component in the switching literature, even fewer trials would contribute to the switch cost calculation for each timing manipulation. Although controlling for all of these factors may be unrealistic, it is important for task switching researchers to be aware of the additional confounds present in the calculation of switch costs.

It is also important to note that after controlling for all of these additional confounds, “true” switch costs are still present (Schmidt & Liefooghe, 2016). Switch costs can still be used as an index of the progress of task-set reconfiguration, and thus endogenous attentional control processes, however they should be considered an impure measure (Monsell, 2017). This may help to explain why finding a relationship between WMC and task switching has been so challenging, both in previous research, and in the present thesis. Although a relationship was found in Experiment 3 when one of these confounds was controlled for (cue switch costs), the relationship was still smaller than might be expected. It may be these additional confounds that help to explain this finding. Such confounds should at least be considered in future research using the task switching paradigm.

5.3.2.2 Task switching analysis techniques.

In addition to considering the design of the task switching paradigm, it is important to consider the analysis techniques used to calculate the index of control processes. It has been argued that previous research has failed to find a relationship between WMC and task switching because of the dependent variable used to measure task switching performance (Draheim et al., 2016). The most common dependent variable used is reaction time difference scores (RT on switch trials minus RT on repeat trials). As discussed in Chapter 2, difference scores are problematic for a variety of reasons. They do not allow for the examination of ACC and RT together (Draheim et al., 2016; Hughes et al., 2014), they tend to have low reliability (Draheim et al., 2016; Edwards, 2001; Hedge et al., 2018; Miller & Ulrich, 2013; Paap & Sawi, 2016) and low variability (Hedge et al., 2018). To account for these issues, alternative methods have been proposed, including the bin scoring method which considers both RT and ACC in the calculation of task switching performance (Hughes et al., 2014).

Across all three experiments in this thesis, both traditional RT difference scores were calculated alongside bin scores. All three experiments replicated previous research by showing that bin scores showed better levels of reliability than traditional difference score calculations (Draheim et al., 2016; Hughes et al., 2014). However, all three experiments failed to find support for the assertion that the reason that previous studies have failed to find a relationship between WMC and task switching was because they had used difference scores instead of bin scores (Draheim et al., 2016). The main analyses of Experiments 1 and 2 failed to find a relationship between WMC and task switching even when bin scores were calculated. In Experiment 3, it looks like a relationship between WMC and task switching was only found when bin scores were analysed, however a relationship was also found when switching performance was calculated using RT difference scores, once outliers were removed from the analysis. It does not appear that the choice of dependent variable is really what is driving the failure to find a relationship here. At least not when standard difference scores are compared to bin scores. Instead, it is more likely that previous research failed to find a relationship between WMC and task switching because they did not control for the confounding effects of cue switch costs. Nonetheless, the increased reliability provided by bin scores, and the fact that they offer an analysis technique that takes into account both RT and ACC makes them a useful measure of task switching performance. Future task switching research should consider using bin scores as a dependent variable.

5.3.3 Using task switching paradigms in individual differences research.

In addition to considering the design and analysis of the switching paradigm, it is important to consider the approach taken by the overall study. In psychological science, there are two main approaches to research questions. One is an experimental approach, and the other is an individual differences approach, or correlational psychology (Cronbach, 1957). Experimental psychology is interested in manipulating variables and examining their effect on cognitive constructs at a general level (e.g., how does everyone switch between tasks). In contrast, individual differences research focusses on how individuals vary on a particular cognitive construct (e.g., examining the range of task switching abilities). These fields have developed fairly independently, but a number of researchers have argued that the merging of these two approaches would be useful for advancing the field of psychological science (Cronbach, 1957; Vogel & Awh, 2008). Although many studies have used experimental tasks when conducting individual differences research (Hedge et al., 2018), it is still considered fairly unusual to combine the two approaches (Engle, 2018). The addition of individual differences approaches to experimental research can be beneficial for theory construction, testing, and development and may help us to better understand underlying cognitive mechanisms (Meier & Kane, 2017; Underwood, 1975; Vogel & Awh, 2008).

Across the three experiments in this thesis, experimental and individual differences approaches were combined to develop a better understanding of task switching, and to test theories of both task switching and WMC. This thesis focussed on two tasks. The complex span WMC tasks used throughout this thesis were designed for individual differences research (Daneman & Carpenter, 1980; Turner & Engle, 1989). In contrast, the task switching paradigm was generated for experimental psychology research (Meiran, 1996; Rogers & Monsell, 1995) This task has been used extensively in the experimental psychology field (Kiesel et al., 2010; Vandierendonck et al., 2010), but it has also less commonly been used to examine individual differences (Butler et al., 2011; Li, Li, Stoet, & Lages, 2019; Miyake & Friedman, 2012; Miyake et al., 2000; Oberauer et al., 2003; von Bastian & Druey, 2017). The experiments in the present thesis have taken this experimental tasks and used it to examine individual differences. An important consideration is whether taking this task from the field of experimental psychology and using it in this way is a wise approach. One should not necessarily assume that just because a task has worked well in experimental psychology and has uncovered robust effects, that it will automatically be useful for an individual differences study (Hedge et al., 2018). We will now explore this consideration.

5.3.3.1 Reliability and variability.

Two important factors to consider when combining individual differences and experimental research methods is reliability and variability (Vogel & Awh, 2008). These two psychometric properties are considered differently in experimental and individual differences research. When we are conducting experimental research, our goal is to have little variability amongst our participants (Hedge et al., 2018). It is beneficial for the data to be homogenous, with every participant showing the same effect. Under such circumstances, we are better able to make conclusions about how cognitive constructs work in a more general way. For example, switching tasks were designed to see what generally happens when we switch between tasks. The goal of these tasks was not to examine the range of abilities in switching. Indeed, task switch costs are an extremely robust and consistent phenomenon and they are easy to replicate (Kiesel et al., 2010; Vandierendonck et al., 2010).

All three experiments in this thesis have consistently shown that task switch costs emerge under a variety of paradigm and design manipulations. This easy replicability is likely because switch costs have low variability. Such homogenous effects are beneficial in experimental psychology research, which treats variability between individuals as error variance, or noise (Cronbach, 1957; Meier & Kane, 2017; Vogel & Awh, 2008). However, one problem with low between subject variability is that it leads to low reliability in finding differences between participants, which is problematic if one wishes to use the task in individual differences research (Cooper, Gonthier, Barch, & Braver, 2017; Hedge et al., 2018; Rouder, Kumar, & Haaf, 2019).

In individual differences research, variability between participants is not thought of as error or noise, but instead, it is desirable (Cronbach, 1957; Hedge et al., 2018; Meier & Kane, 2017). Since the goal of this kind of research is to distinguish between individuals, high variability between subjects is beneficial. We do not want homogenous data in individual differences research, as the more variability in our participants, the more reliable we will be in consistently ranking them (Cooper et al., 2017; Hedge et al., 2018). Clearly, the goals of experimental and individual differences research are slightly different, which means that they may require different tasks for accurate measurement. Given all of this, it is extremely important that when we take an experimental psychology task and use it in an individual differences study, that we consider the variability and reliability of the measure.

Task switching tasks are of particular concern because the primary dependent variable on switching tasks is RT difference scores. Difference scores in general tend to have low variance (Hedge et al., 2018) and low reliability (Draheim et al., 2016; Edwards, 2001; Hedge et al., 2018; Hughes et al., 2014; Miller & Ulrich, 2013; Paap & Sawi, 2016). A measure with low reliability is not particularly useful in correlational research as the reliability of a variable will attenuate the magnitude of any correlation observed between two variables (Hedge et al., 2018; Paap & Sawi, 2016). To draw accurate inferences about a relationship, it is important to know the reliability of the measures. Despite its importance, in cognitive psychology it is rare for researchers to report the reliability of the measures that are being used (Cooper et al., 2017; Hughes et al., 2014; Parsons, Kruijt, & Fox, 2019). Recently, it has been suggested that across both experimental and individual differences research, it should become a standard practice to report the reliability of all behavioural measures (Parsons et al., 2019).

A wide range of reliability estimates of switch costs have been reported in the literature (Hughes et al., 2014). For example, looking at internal consistency reliability, Salthouse, Fristoe, McGuthry, and Hambrick (1998) found RT switch cost split-half reliability estimates of .46, .61, and .71 using different task switching paradigms with different stimuli. Others have found split-half reliability estimates of .59 and .91 (Miyake et al., 2000) or .63 and .73 for RT switch costs (Draheim et al., 2016) across different switching paradigms. Cronbach’s alpha switch cost reliabilities ranging from .38 to .81 have been reported across different timing manipulations on the switching paradigm. This is quite a wide range of reliability estimates, many of which fall below the recommended acceptable level of .70. For basic research, when examining a hypothesized measure of a construct, reliability levels of .70 or higher are recommended (Nunnally, 1978).

Similarly, across the present thesis, a range of reliability estimates were found. In Experiment 1, reliability estimates of the overall RT switch costs across the three switching paradigms ranged from .69 to .75. Similarly, in Experiment 2, they ranged from .72 to .78, thus falling within, or close to acceptable levels of reliability. In Experiment 3, when task switch costs were separated from cue switch costs, the RT switch cost reliability estimate fell to .58, which is a possible concern. Across all three experiments, reliability estimates increased when bin scores were considered, with bin score reliability estimates ranging from .70 to .82 across the three experiments. An interesting finding was how low the reliability of accuracy switch costs were. Across the three experiments in this thesis, accuracy switch cost reliability estimates ranged from .16 to .66. These low reliability estimates replicate findings from previous studies (Hughes et al., 2014), and suggest that accuracy switch costs should not be used in individual differences research. In contrast, RT switch costs and bin scores showed acceptable or close to acceptable reliability levels.

It is important for future research interested in using experimental psychology tasks in individual differences research to consider the reliability of these tasks. The psychometric properties can have a large bearing on whether a relationship is found between the variables of interest. Given that the reliability levels of the switching task in Experiments 1 and 2 approached acceptable levels, it is unlikely that this could fully explain our failure to find a relationship between WMC and task switching. It seems more likely that the failure to find a relationship between these constructs in the earlier experiments was due to the confounding effects of cue switch costs. However, reliability of the measure certainly would have contributed to some degree. The correlations certainly would have been attenuated by this (Hedge et al., 2018), and ideally we would want reliability levels as close to 1 as possible. In Experiment 3, reliability levels were slightly lower than in Experiments 1 and 2. Given this, caution should be taken when interpreting the results. It is possible that the correlation that we found between WMC and switching could be due to measurement error. However, the bin score reliability estimate did meet acceptable levels, and the correlation was found with this dependent variable as well as the RT switch costs, which had lower reliability levels. Given this, we can be fairly confident that the findings of Experiment 3 are not due solely to the low reliability of the switching measures. However, the correlation found may be of a smaller magnitude than the true correlation between WMC and task switching due to the low reliability of the switch cost measures. I agree that it will be important for future research using cognitive tasks to adopt the standard practice of considering and reporting measurement reliability (Parsons et al., 2019).

5.3.3.2 Outliers.

Another important consideration for future research combining experimental and individual differences approaches is to consider the role of outliers. Traditionally, in the task switching literature trial-level RT outliers are consistently considered (e.g., trials with an RT less than or greater than a certain value are excluded) (e.g., Mayr & Kliegl, 2000; Rogers & Monsell, 1995). However, it is less common for such research to exclude participants with particularly low or high switch costs, which may be statistical outliers. However, when conducting correlational/individual differences research, it becomes more important to consider the role of these participant-level outliers (Goodwin & Leech, 2006). One limitation of the present experiments is that although it was pre-registered exactly how trial-level RT outliers would be dealt with, outlier removal at the participant level was not pre-registered. Opinions differ regarding exactly what to do with outliers (Osborne & Overbay, 2004), and information about defining and dealing with outliers is largely inconsistent, with a range of methods used across laboratories, often in non-transparent ways (Aguinis, Gottfredson, & Joo, 2013). Deciding how to define outliers, and deciding whether or not to exclude outliers after seeing the data is a questionable research practice (Bakker & Wicherts, 2014; John, Loewenstein, & Prelec, 2012). Given this, across all three experiments, results are reported with outliers included. This is potentially problematic given the impact that outliers can have on correlations (Goodwin & Leech, 2006).

Outliers were not investigated in Experiments 1 and 2, however, when scatterplots of the relationship between WMC and task switching in Experiment 3 were examined, a couple of data points jumped out as clear outliers. In light of this, results were re-run with these outliers removed, and this changed the conclusions about the relationship between WMC and RT switch costs quite considerably. Given that this outlier removal was not pre-registered, the inferences should be interpreted with caution. However, the fact that the relationship between WMC and task switching was replicated in the bin score analysis, which did not have any outliers bolsters the conclusion that a relationship between WMC and task switching emerges when cue switch costs are controlled for.

After running the results of Experiment 3 with outliers included and excluded, for consistency, the same approach was taken for Experiments 1 and 2. When outliers were removed, some changes regarding the magnitude and significance of the correlations did take place. These changes were largely restricted to the exploratory subgroup analyses from Experiment 1 which were severely underpowered for individual differences research. Given the small sample sizes in these exploratory analyses, it is not surprising that the removal of outliers led to changes in the correlations. However, the pattern of results, and the inferences and conclusions made for both Experiment 1 and 2 remained consistent across both the outlier included and excluded analyses. A direct comparison of these analyses is available upon request. It is recommended that future research pre-register both trial-level and participant-level outlier removal.

5.4 Recommendations for Future Research

The results of this thesis have begun to explore the relationship between WMC and task switching, however there is still a great deal that we do not yet understand. With regard to the task switching paradigm specifically, it will be important for future research to continue investigating exactly what task switch costs index. Future research looking at the relationship between task switching and WMC would benefit from further exploring the role of strategy use in task switching, the difficulty of the switching paradigm, and the ecological validity of the chosen switching task. In this final section, potential ideas for exploring these factors will be discussed.

5.4.1 Strategy use.

Future experiments that use task switching performance as an index of attentional control must take strategy use into account. In experimental psychology the emphasis has been on the study of ability on experimental tasks. In contrast, strategy use has been studied much less frequently (Irons & Leber, 2018). However, the study of strategy use is imperative for developing a clear understanding of exactly what the task is measuring. This is especially the case for task switching paradigms, when the choice of strategy determines the degree of attentional control that is recruited to perform the task (Forrest et al., 2014). If participants implement a task set strategy, switch costs likely reflect attentional control processes (Monsell, 2003, 2017). However, if they choose a compound-cue retrieval strategy, they may be able to perform the task using an associative learning approach, which would not require attentional control (Logan & Bundesen, 2003, 2004; Logan & Schneider, 2010; Schneider & Logan, 2005). Although choosing an associative compound retrieval strategy is not necessarily beneficial for task performance, nor does it make the task easier, it seems that some participants still choose such a strategy, at least on a subset of trials (Forrest et al., 2014). These findings fit well with other research on strategy use which has shown that participants often choose non-optimal strategies on attentional control tasks (Irons & Leber, 2016).

It is important that we do not make assumptions about the strategies that participants use when completing the switching task. Individual differences in attentional control strategies have been shown on visual search tasks (Irons & Leber, 2016, 2018), providing evidence that participants do not approach these kinds of tasks in exactly the same way. It has long been the tradition in switching research to assume that participants are all using a task set strategy, but this may have led us to overlook a potentially interesting phenomenon. Studies have attempted to prevent alternative strategies by using large stimulus sets, however it is possible that participants may still combine similar stimuli and implement an associative learning strategy under such conditions. Given this, it will be important to measure strategy use across all switching tasks.

The development of a standardized way of measuring strategy use will be important for future task switching research. The results of Experiment 3 (Chapter 4) provide a starting point for such an endeavour. However, more extensive research will be needed to develop a list of questions that cover the range of strategy decisions that participants can make on the switching paradigm. The development of such a resource will allow future studies interested in exploring attentional control to exclude participants who have not used strategies that recruit control processes. Given that attentional control strategies seem to be a trait-like quality (Irons & Leber, 2018), this is also an interesting avenue for future individual differences research. Is there something different about participants who choose a task set strategy over an associative learning strategy? Are there differences in their overall attentional control abilities? It would be hypothesized that task switching performance would be related to WMC only in those participants who implement a task set strategy. In contrast, those who use associative learning and memory based strategies would not show a relationship with WMC. Only future research will be able to shed light on these interesting questions.

5.4.2 Task difficulty.

Another area for future research to explore is the manipulation of task difficulty on the switching paradigm. Across a variety of other tasks, research has shown that WMC is related to attentional control only when the tasks are particularly taxing (Kane & Engle, 2003; Poole & Kane, 2009; Robison et al., 2018). This was examined in Experiment 2 (Chapter 3). Although participants subjectively reported that the switching task was more difficult under auditory distraction, suggesting that the task difficulty manipulation was successful, it had no influence on RT switch costs. This is quite an interesting finding that warrants further investigation. In Experiment 2, auditory distraction was used to tax attentional control because it did not require an additional response from the participant. Requiring a secondary response may alter the way in which the switching paradigm is completed. However, choosing a task with no response requirements had no effect on RT switch costs. To more fully tax attentional control, and influence switch costs, adding a secondary task which actually requires a response may be important.

Which secondary task to choose is quite a challenge. To really tax attentional control, the random number generation task (Evans, 1978) may be an ideal task as it draws heavily on executive control functions (Jahanshahi, Saleem, Ho, Dirnberger, & Fuller, 2006; Sexton & Cooper, 2014), with task performance requiring inhibition, memory updating, monitoring (Baddeley et al., 1998; Miyake et al., 2000; Peters, Giesbrecht, Jelicic, & Merckelbach, 2007; Sexton & Cooper, 2014), and switching (Baddeley et al., 1998; Sexton & Cooper, 2014). Random number generation and task switching appear to recruit the same resources for task performance, with RNG impairing accuracy and reaction time performance on switching tasks (Baddeley et al., 2001), and concurrent switching impairing random number generation performance (Baddeley et al., 1998; Cooper, Wutke, & Davelaar, 2012). Additionally, the random number generation task has been used as an additional task in previous research to manipulate cognitive/attentional load (Schmitz, Teige-Mocigemba, Voss, & Klauer, 2013; Wierzchoń, Gaillard, Asanowicz, & Cleeremans, 2012). Given all of this, the random number generation task seems like an ideal starting point for taxing attentional control more fully on the switching task.

Previous research has shown that switch costs can increase when the random number generation task is performed alongside the switching task, however this has only been shown using the list paradigm (Baddeley et al., 2001). The list paradigm merely compares the time to complete a list of the same task versus a list with alternating tasks. In contrast, on the explicitly cued switching paradigm, RT comparisons are made across a series of trials. In pilot work for Experiment 2, I had participants complete a random number generation task while doing the switching paradigm. However, it became quickly apparent that participants found this extremely challenging. Although this was the goal, the problem was that switch costs seemed to decrease rather than increase with the concurrent task. Participants were altering the timing of their responses on the switching task in order to make their responses on the random number generation task, and thus the switching task was no longer measuring the cost of switching tasks. Given time constraints, it was decided to choose a less taxing auditory distraction paradigm which did not require a response from participants. This prevented the secondary task from directly altering primary task performance. However, the results of Experiment 2 suggest that the auditory distraction task did not tax attentional control enough to alter RT switch costs.

It would be interesting for future research to look into ways of adding a demanding secondary task like random number generation to the switching task without altering how participants complete the primary task. Looking at the relationship between WMC and task switching under such extremely cognitively demanding conditions while also controlling for the confounding effects of cue switch costs would be interesting. An even stronger relationship between WMC and task switching would be expected. In such an experiment, it may also be useful to measure subjective reports of task difficulty alongside more objective measures, such as pupil dilation. Pupil dilation can serve as a useful index of mental effort (Heitz, Schrock, Payne, & Engle, 2008; van der Wel & van Steenbergen, 2018). In switching tasks, increasing the demands of the task leads to increases in pupil dilation (van der Wel & van Steenbergen, 2018). Having this objective measure would make the researcher more confident about whether the task difficulty manipulation was successful.

5.4.3 Ecological validity.

Finally, it would be interesting for future research examining the relationship between WMC and task switching to see how this relationship changes when a more ecologically valid measure of task switching is implemented. Throughout this chapter, the methodological pitfalls of using the traditional switching paradigm as an index of attentional control in individual differences research have been highlighted. A real world implementation of task switching may overcome some of these pitfalls and better highlight the role of attentional control in switching. The WMC correlates of another cognitive construct; mind wandering have been shown to differ depending on whether measurements are taken in an artificial laboratory setting versus in the real world (Kane et al., 2017). Such findings have important implications for theories of mind wandering that have been generated based on laboratory findings (Kane et al., 2017). Like task switching, the field of mind wandering has struggled with deciding on a standardized way of how to assess this cognitive construct (Weinstein, 2018). It would be useful for future research to see whether, like mind wandering, real world task switching is differentially related to WMC when compared with laboratory task switching.

In a related area of research, WMC has been associated with more ecologically valid measures of multitasking (Hambrick et al., 2010; Konig et al., 2005; Liu et al., 2016; Pollard & Courage, 2017; Redick, 2016; Redick et al., 2016). These experiments have used tasks such as the cooking a virtual breakfast task (Pollard & Courage, 2017) which involves cooking five different foods which all have different start times, monitoring the cooking, and also setting a virtual table at the same time. Such a task involves making a plan, executing that plan, as well as keeping a goal in mind while executing sub-goals. Another popular virtual reality multitasking paradigm is the Edinburgh virtual errands test (Chen & Hsieh, 2018; Logie, Law, Trawley, & Nissan, 2010). On this task, participants are required to run a series of errands while wandering through a simulated environment. This task requires a range of cognitive components including planning, execution, sustained attention, working memory, prospective memory, processing speed, and task switching (Chen & Hsieh, 2018). Although these tasks serve as excellent ecologically valid measures of real life multitasking, the fact that they measure so many different cognitive constructs makes it difficult to know which aspect of the task contributes to their relationship with WMC.

It would be interesting to develop an ecologically valid version of the switching task which remains somewhat true to the laboratory based paradigm. The goal of such a task would be to isolate the attentional control component of switching. This would come with some challenges, as even in a virtual context, participants will need to be told when to switch tasks, and such cuing will confound the cost of switching. Even if a voluntary version of the task is used, and participants choose when to switch tasks, internal cueing will confound switch costs (Mayr, 2010). However, as long as such factors are taken into account and controlled for, an ecologically valid version of the switching paradigm would help to extend this area of study. It will be interesting for future research to see whether altering the ecological validity of the task will change its relationship with WMC, as has been seen with mind wandering (Kane et al., 2017).

5.5 Conclusion

Across three experiments, this thesis has attempted to explore the elusive relationship between WMC and task switching. These cognitive constructs have been studied extensively individually, however there has been comparatively little research looking at the relationship between these tasks (Liefooghe et al., 2008; Vandierendonck, 2016). Some have argued that working memory can be studied independently of other

EFs, suggesting that it is not necessary for a good theory of working memory to consider or explain phenomena associated with task switching (Oberauer et al., 2018). In contrast, others have argued that studying task switching and working memory together is imperative to developing a more clear understanding of these constructs (Vandierendonck, 2018). I agree with the latter argument. It is vital to develop a better understanding of task switching and WMC, and the ways in which they interact to further our theoretical understanding of executive functioning in general, and task switching and WMC specifically. This thesis has provided a step in this direction.

I have shown across three experiments that the relationship between task switching and WMC is difficult to find. No relationship between these constructs was found across a variety of traditional switching paradigms (Experiment 1), or when task difficulty was manipulated (Experiment 2). However, when cue switch costs were controlled for, a relationship between these constructs was identified (Experiment 3). These results point to the importance of making careful experimental design decisions when using the task switching paradigm in individual differences research. The present thesis has extended our knowledge regarding the relationship between WMC and task switching, and has provided suggestions for new research questions to further extend this field.

References

Abrahamse, E., Braem, S., Notebaert, W., & Verguts, T. (2016). Grounding cognitive control in associative learning. *Psychological Bulletin, 142*(7), 693-728.

Aguinis, H., Gottfredson, R. K., & Joo, H. (2013). Best-practice recommendations for defining, identifying, and handling outliers. *Organizational Research Methods, 16*(2), 270-301.

Ahmed, L., & De Fockert, J. W. (2012). Focusing on attention: The effects of working memory capacity and load on selective attention. *PloS one, 7*(8), e43101.

Allport, A., Styles, E., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta, & M. Moscovitch (Eds.), *Attention and Performance XV: Conscious and Nonconscious Information Processing* (pp. 421-452). Cambridge, MA: The MIT Press.

Allport, A., & Wylie, G. (2000). Task switching, stimulus-response bindings, and negative priming. In S. Monsell, & J. Driver (Eds.), *Control of Cognitive Processes: Attention and Performance XVIII* (pp. 35-70). Cambridge, MA: MIT Press.

Altmann, E. M. (2002). Functional decay of memory for tasks. *Psychological Research, 66*(4), 287-297.

Altmann, E. M. (2003). Task switching and the pied homunculus: Where are we being led? *Trends in Cognitive Sciences, 7*(8), 340-341.

Altmann, E. M. (2004a). Advance preparation in task switching: What work is being done? *Psychological Science, 15*(9), 616-622.

Altmann, E. M. (2004b). The preparation effect in task switching: Carryover of SOA. *Memory & Cognition, 32*(1), 153-163.

Altmann, E. M. (2006). Task switching is not cue switching. *Psychonomic Bulletin & Review, 13*(6), 1016-1022.

Altmann, E. M. (2007). Comparing switch costs: Alternating runs and explicit cuing. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 33*(3), 475-483.

Altmann, E. M., & Gray, W. D. (2008). An integrated model of cognitive control in task switching. *Psychological Review, 115*(3), 602-639.

Anderson, J. R., Reder, L. M., & Lebiere, C. (1996). Working memory: Activation limitations on retrieval. *Cognitive Psychology, 30*(3), 221-256.

Arrington, C. M., & Logan, G. D. (2004). The cost of a voluntary task switch. *Psychological Science, 15*(9), 610-615.

Arrington, C. M., & Logan, G. D. (2005). Voluntary task switching: Chasing the elusive homunculus. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 31*(4), 683-702.

Arrington, C. M., Logan, G. D., & Schneider, D. W. (2007). Separating cue encoding from target processing in the explicit task-cuing procedure: Are there "true" task switch effects? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(3), 484-502.

Arrington, C. M., Reiman, K. M., & Weaver, S. M. (2014). Voluntary task switching. In J. A. Grange, & G. Houghton (Eds.), *Task Switching and Cognitive Control* (pp. 117-136). Oxford: Oxford University Press.

Baddeley, A. (1992). Working memory. *Science, 255*(5044), 556-559.

Baddeley, A. (1996). Exploring the central executive. *The Quarterly Journal of Experimental Psychology: Section A, 49*(1), 5-28.

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4*(11), 417-423.

Baddeley, A. (2002). Fractionating the central executive. In D. T. Stuss, & R. T. Knight (Eds.), *Principles of Frontal Lobe Function* (pp. 246-260). New York: Oxford University Press.

Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience, 4*(10), 829-839.

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology, 63*, 1-29.

Baddeley, A., Chincotta, D., & Adlam, A. (2001). Working memory and the control of action: Evidence from task switching. *Journal of Experimental Psychology. General*, *130*(4), 641-657.

Baddeley, A., Emslie, H., Kolodny, J., & Duncan, J. (1998). Random generation and the executive control of working memory. *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology, 51*(4), 819-852.

Baddeley, A., & Hitch, G. (1974). Working Memory. In G. H. Bower (Ed.), *The Psychology of Learning and Motivation: Advances in Research and Theory* (Vol. 8, pp. 47-89). New York: Academic Press.

Bakker, M., & Wicherts, J. M. (2014). Outlier removal and the relation with reporting errors and quality of psychological research. *PLoS One*, *9*(7), e103360.

Banbury, S., & Berry, D. C. (1998). Disruption of office-related tasks by speech and office noise. *British Journal of Psychology, 89*(3), 499-517.

Barrett, L. F., Tugade, M. M., & Engle, R. W. (2004). Individual differences in working memory capacity and dual-process theories of the mind. *Psychological Bulletin, 130*(4), 553-573.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology. General, 133*(1), 83-100.

Bell, R., Dentale, S., Buchner, A., & Mayr, S. (2010). ERP correlates of the irrelevant sound effect. *Psychophysiology, 47*(6), 1182-1191.

Blair, C. (2017). Educating executive function. *Wiley Interdisciplinary Reviews. Cognitive Science, 8*(1-2).

Bleckley, M. K., Durso, F. T., Crutchfield, J. M., Engle, R. W., & Khanna, M. M. (2003). Individual differences in working memory capacity predict visual attention allocation. *Psychonomic Bulletin & Review, 10*(4), 884-889.

Bleckley, M. K., Foster, J. L., & Engle, R. W. (2015). Working memory capacity accounts for the ability to switch between object-based and location-based allocation of visual attention. *Memory & Cognition, 43*(3), 379-388.

Blum, D., & Holling, H. (2017). Spearman's law of diminishing returns. A meta-analysis. *Intelligence, 65*, 60-66.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624-652.

Braem, S. (2017). Conditioning task switching behavior. *Cognition, 166*, 272-276.

Braem, S., & Egner, T. (2018). Getting a grip on cognitive flexibility. *Current Directions in Psychological Science, 27*(6), 470-476.

Brass, M., & von Cramon, D. Y. (2004). Decomposing components of task preparation with functional magnetic resonance imaging. *Journal of Cognitive Neuroscience, 16*(4), 609-620.

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. In A. Conway, C. Jarrold, M. Kane, A. Miyake, & J. Towse (Eds.), *Variation in Working Memory* (pp. 76-106). New York: Oxford University Press.

Braver, T. S., Reynolds, J. R., & Donaldson, D. I. (2003). Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron*, *39*(4), 713-726.

Brewin, C., & Beaton, A. (2002). Thought suppression, intelligence, and working memory capacity. *Behaviour Research and Therapy*, *40*(8), 923-930.

Brydges, C. R., Gignac, G. E., & Ecker, U. K. (2018). Working memory capacity, short-term memory capacity, and the continued influence effect: A latent-variable analysis. *Intelligence*, *69*, 117-122.

Brysbaert, M., & New, B. (2009). Moving beyond Kučera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior research methods, 41*(4), 977-990.

Bugg, J. M., & Crump, M. J. (2012). In support of a distinction between voluntary and stimulus-driven control: A review of the literature on proportion congruent effects. *Frontiers in Psychology, 3,* 1-16.

Butler, K. M., Arrington, C. M., & Weywadt, C. (2011). Working memory capacity modulates task performance but has little influence on task choice. *Memory & Cognition, 39*(4), 708-724.

Button, K. S., Ioannidis, J. P., Mokrysz, C., Nosek, B. A., Flint, J., Robinson, E. S., & Munafò, M. R. (2013). Power failure: Why small sample size undermines the reliability of neuroscience. *Nature Reviews Neuroscience*, *14*(5), 365-376.

Callard, F., Smallwood, J., Golchert, J., & Margulies, D. S. (2013). The era of the wandering mind? Twenty-first century research on self-generated mental activity. *Frontiers in Psychology, 4,* 891.

Campbell, T. (2005). The cognitive neuroscience of auditory distraction. *Trends in Cognitive Sciences, 9*(1), 3-5.

Case, R., Kurland, D. M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology, 33*(3), 386-404.

Cassidy, G., & MacDonald, R. A. (2007). The effect of background music and background noise on the task performance of introverts and extraverts. *Psychology of Music, 35*(3), 517-537.

Chan, R. C., Shum, D., Toulopoulou, T., & Chen, E. Y. (2008). Assessment of executive functions: Review of instruments and identification of critical issues. *Archives of Clinical Neuropsychology, 23*(2), 201-216.

Chen, Y. Q., & Hsieh, S. (2018). The relationship between internet-gaming experience and executive functions measured by virtual environment compared with conventional laboratory multitasks. *PLoS One, 13*(6), e0198339.

Christoff, K., Mills, C., Andrews-Hanna, J. R., Irving, Z. C., Thompson, E., Fox, K. C. R., & Kam, J. W. Y. (2018). Mind-Wandering as a Scientific Concept: Cutting through the Definitional Haze. *Trends in Cognitive Sciences, 22*(11), 957-959.

Cohen, J. D. (2017). Cognitive control: Core constructs and current considerations. In T. Egner (Ed.), *The Wiley Handbook of Cognitive Control* (pp. 2-28). Oxford: John Wiley & Sons.

Cole, M. W., & Schneider, W. (2007). The cognitive control network: Integrated cortical regions with dissociable functions. *Neuroimage, 37*(1), 343-360.

Collette, F., Van der Linden, M., Laureys, S., Delfiore, G., Degueldre, C., Luxen, A., & Salmon, E. (2005). Exploring the unity and diversity of the neural substrates of executive functioning. *Human Brain Mapping, 25*(4), 409-423.

Colom, R., Martínez-Molina, A., Shih, P. C., & Santacreu, J. (2010). Intelligence, working memory, and multitasking performance. *Intelligence, 38*(6), 543-551.

Conway, A. R., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin & Review, 8*(2), 331-335.

Conway, A. R., & Engle, R. W. (1996). Individual differences in working memory capacity: More evidence for a general capacity theory. *Memory, 4*(6), 577-590.

Conway, A. R., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review, 12*(5), 769-786.

Cooper, R. P., Wutke, K., & Davelaar, E. J. (2012). Differential contributions of set-shifting and monitoring to dual-task interference. *The Quarterly Journal of Experimental Psychology, 65*(3), 587-612.

Cooper, S. R., Gonthier, C., Barch, D. M., & Braver, T. S. (2017). The role of psychometrics in individual differences research in cognition: A case study of the AX-CPT. *Frontiers in Psychology, 8*, 1482.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104*(2), 163-191.

Cowan, N. (1995). *Attention and Memory: An Integrated Framework*. New York: Oxford University Press.

Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake, & P. Shah (Eds.), *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control* (pp. 62-101). Cambridge: Cambridge University Press.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *The Behavioral and Brain Sciences, 24*(1), 87-114.

Cowan, N. (2008). What are the differences between long-term, short-term, and working memory? *Progress in Brain Research, 169,* 323-338.

Cowan, N., Elliott, E. M., Scott Saults, J., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology, 51*(1), 42-100.

Cronbach, L. J. (1957). The two disciplines of scientific psychology. *American Psychologist, 12*(11), 671-684.

Dajani, D. R., & Uddin, L. Q. (2015). Demystifying cognitive flexibility: Implications for clinical and developmental neuroscience. *Trends in Neurosciences, 38*(9), 571-578.

Dalton, P., & Hughes, R. W. (2014). Auditory attentional capture: Implicit and explicit approaches. *Psychological Research, 78*(3), 313-320.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*(4), 450-466.

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: A meta-analysis. *Psychonomic Bulletin & Review, 3*(4), 422-433.

De Baene, W., & Brass, M. (2011). Cue-switch effects do not rely on the same neural systems as task-switch effects. *Cognitive, Affective & Behavioral Neuroscience, 11*(4), 600-607.

De Baene, W., & Brass, M. (2014). Dissociating strategy-dependent and independent components in task preparation. *Neuropsychologia*, *62*, 331-340.

De Jong, R. (2000). An intention-activation account of residual switch costs. In S. Monsell, & J. Driver (Eds.), *Control of Cognitive Processes: Attention and Performance XVIII* (pp. 357-376). Cambridge: MIT Press.

De Jong, R. (2001). Adult age differences in goal activation and goal maintenance. *European Journal of Cognitive Psychology, 13*(1-2), 71-89.

Derrfuss, J., Brass, M., & von Cramon, D. Y. (2004). Cognitive control in the posterior frontolateral cortex: Evidence from common activations in task coordination, interference control, and working memory. *Neuroimage, 23*(2), 604-612.

Detterman, D. K., & Daniel, M. H. (1989). Correlations of mental tests with each other and with cognitive variables are highest for low IQ groups. *Intelligence, 13*(4), 349-359.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64,* 135-168.

Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental Cognitive Neuroscience, 18*, 34-48.

Draheim, C., Harrison, T. L., Embretson, S. E., & Engle, R. W. (2018). What item response theory can tell us about the complex span tasks. *Psychological Assessment, 30*(1), 116-129.

Draheim, C., Hicks, K. L., & Engle, R. W. (2016). Combining Reaction Time and Accuracy: The Relationship Between Working Memory Capacity and Task Switching as a Case Example. *Perspectives on Psychological Science, 11*(1), 133-155.

Duchek, J. M., Balota, D. A., Tse, C.-S., Holtzman, D. M., Fagan, A. M., & Goate, A. M. (2009). The utility of intraindividual variability in selective attention tasks as an early marker for Alzheimer's disease. *Neuropsychology, 23*(6), 746-758.

Edwards, J. R. (2001). Ten difference score myths. *Organizational Research Methods, 4*(3), 265-287.

Emerson, M. J., & Miyake, A. (2003). The role of inner speech in task switching: A dual-task investigation. *Journal of Memory and Language, 48*(1), 148-168.

Engle, R. W. (2001). What is working memory capacity. In H. L. Roediger, & J. S. Nairne (Eds.), *The Nature of Remembering: Essays in Honor of Robert G. Crowder* (pp. 297-314). Washington, DC.: Americal Psychological Association.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11*(1), 19-23.

Engle, R. W. (2018). Working Memory and Executive Attention: A Revisit. *Perspectives on Psychological Science, 13*(2), 190-193.

Engle, R. W., Carullo, J. J., & Collins, K. W. (1991). Individual differences in working memory for comprehension and following directions. *The Journal of Educational Research, 84*(5), 253-262.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. *Psychology of Learning and Motivation: Advances in Research and Theory, 44*, 145-199.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology. General, 128*(3), 309-331.

Evans, F. J. (1978). Monitoring attention deployment by random number generation: An index to measure subjective randomness. *Bulletin of the Psychonomic Society, 12*(1), 35-38.

Faraco, C. C., Unsworth, N., Langley, J., Terry, D., Li, K., Zhang, D., . . . Miller, L. S. (2011). Complex span tasks and hippocampal recruitment during working memory. *Neuroimage, 55*(2), 773-787.

Farooqui, A. A., & Manly, T. (2015). Anticipatory control through associative learning of subliminal relations: Invisible may be better than visible. *Psychological Science, 26*(3), 325-334.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175-191.

Felez-Nobrega, M., Foster, J. L., Puig-Ribera, A., Draheim, C., & Hillman, C. H. (2018). Measuring working memory in the Spanish population: Validation of a multiple shortened complex span task. *Psychological Assessment, 30*(2), 274-279.

Forrest, C. L., Monsell, S., & McLaren, I. P. (2014). Is performance in task-cuing experiments mediated by task set selection or associative compound retrieval? *Journal of Experimental Psychology. Learning, Memory, and Cognition, 40*(4), 1002-1024.

Forstmann, B. U., Brass, M., & Koch, I. (2007). Methodological and empirical issues when dissociating cue-related from task-related processes in the explicit task-cuing procedure. *Psychological Research, 71*(4), 393-400.

Foster, J. L., Shipstead, Z., Harrison, T. L., Hicks, K. L., Redick, T. S., & Engle, R. W. (2015). Shortened complex span tasks can reliably measure working memory capacity. *Memory & Cognition, 43*(2), 226-236.

Friedman, N. P., & Miyake, A. (2017). Unity and diversity of executive functions: Individual differences as a window on cognitive structure. *Cortex, 86*, 186-204.

Furley, P. A., & Memmert, D. (2012). Working memory capacity as controlled attention in tactical decision making. *Journal of Sport & Exercise Psychology, 34*(3), 322-344.

Gamboz, N., Borella, E., & Brandimonte, M. A. (2009). The role of switching, inhibition and working memory in older adults' performance in the Wisconsin Card Sorting Test. *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition, 16*(3), 260-284.

Golchert, J., Smallwood, J., Jefferies, E., Seli, P., Huntenburg, J. M., Liem, F., . . . Margulies, D. S. (2017). Individual variation in intentionality in the mind-wandering state is reflected in the integration of the default-mode, fronto-parietal, and limbic networks. *Neuroimage, 146*, 226-235.

Gonthier, C., Thomassin, N., & Roulin, J. L. (2016). The composite complex span: French validation of a short working memory task. *Behavior Research Methods, 48*(1), 233-242.

Goodwin, L. D., & Leech, N. L. (2006). Understanding correlation: Factors that affect the size of r. *The Journal of Experimental Education, 74*(3), 249-266.

Grange, J. A., & Houghton, G. (2010). Cue-switch costs in task-switching: Cue priming or control processes? *Psychological Research, 74*(5), 481-490.

Grange, J. A., & Houghton, G. (2014). Task switching and cognitive control: An introduction. In J. A. Grange, & G. Houghton (Eds.), *Task Switching and Cognitive Control* (pp. 1-26). Oxford: Oxford University Press.

Hambrick, D. Z., & Altmann, E. M. (2015). The role of placekeeping ability in fluid intelligence. *Psychonomic Bulletin & Review, 22*(4), 1104-1110.

Hambrick, D. Z., Oswald, F. L., Darowski, E. S., Rench, T. A., & Brou, R. (2010). Predictors of multitasking performance in a synthetic work paradigm. *Applied Cognitive Psychology, 24*(8), 1149-1167.

Hedge, C., Powell, G., & Sumner, P. (2018). The reliability paradox: Why robust cognitive tasks do not produce reliable individual differences. *Behavior Research Methods, 50*(3), 1166-1186.

Heitz, R. P., Schrock, J. C., Payne, T. W., & Engle, R. W. (2008). Effects of incentive on working memory capacity: Behavioral and pupillometric data. *Psychophysiology, 45*(1), 119-129.

Hester, R., & Garavan, H. (2005). Working memory and executive function: The influence of content and load on the control of attention. *Memory & Cognition, 33*(2), 221-233.

Horoufchin, H., Philipp, A. M., & Koch, I. (2011). The dissipating task-repetition benefit in cued task switching: task-set decay or temporal distinctiveness? *Journal of Experimental Psychology: Human Perception and Performance, 37*(2), 455-472.

Howell, D. C. (2010). *Statistical Methods for Psychology* (Seventh Edition ed.). Belmont, CA: Wadsworth.

Hughes, M. M., Linck, J. A., Bowles, A. R., Koeth, J. T., & Bunting, M. F. (2014). Alternatives to switch-cost scoring in the task-switching paradigm: Their reliability and increased validity. *Behavior Research Methods, 46*(3), 702-721.

Hughes, R. W. (2014). Auditory distraction: A duplex-mechanism account. *PsyCh Journal, 3*(1), 30-41.

Hughes, R. W., Hurlstone, M. J., Marsh, J. E., Vachon, F., & Jones, D. M. (2013). Cognitive control of auditory distraction: Impact of task difficulty, foreknowledge, and working memory capacity supports duplex-mechanism account. *Journal of Experimental Psychology: Human Perception and Performance, 39*(2), 539-553.

Hughes, R. W., Vachon, F., & Jones, D. M. (2007). Disruption of short-term memory by changing and deviant sounds: Support for a duplex-mechanism account of auditory distraction. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(6), 1050-1061.

Hultsch, D. F., MacDonald, S. W., & Dixon, R. A. (2002). Variability in reaction time performance of younger and older adults. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 57*(2), 101-115.

Ioannidis, J. P. (2008). Why most discovered true associations are inflated. *Epidemiology,* 640-648.

Irons, J. L., & Leber, A. B. (2016). Choosing attentional control settings in a dynamically changing environment. *Attention, Perception, & Psychophysics, 78*(7), 2031-2048.

Irons, J. L., & Leber, A. B. (2018). Characterizing individual variation in the strategic use of attentional control. *Journal of Experimental Psychology: Human Perception and Performance, 44*(10), 1637-1654.

Jahanshahi, M., Saleem, T., Ho, A. K., Dirnberger, G., & Fuller, R. (2006). Random number generation as an index of controlled processing. *Neuropsychology, 20*(4), 391-399.

Jensen, A. R. (1992). The importance of intraindividual variation in reaction time. *Personality and Individual Differences, 13*(8), 869-881.

Jersild, A. T. (1927). Mental set and shift. *Archives of psychology, No. 89*.

John, L. K., Loewenstein, G., & Prelec, D. (2012). Measuring the prevalence of questionable research practices with incentives for truth telling. *Psychological science, 23*(5), 524-532.

Jones, D. M., Banbury, S. P., Tremblay, S., & Macken, W. J. (1999). The effect of task-irrelevant sounds on cognitive performance. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 43*(3), 261-265.

Jones, D. M., Hughes, R. W., & Macken, W. J. (2010). Auditory distraction and serial memory: The avoidable and the ineluctable. *Noise and Health, 12*(49), 201-209.

Jones, D. M., & Macken, W. J. (1993). Irrelevant tones produce an irrelevant speech effect: Implications for phonological coding in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19*(2), 369-381.

Jost, K., De Baene, W., Koch, I., & Brass, M. (2013). A review of the role of cue processing in task switching. *Zeitschrift Fur Psychologie-Journal of Psychology, 221*(1), 5-14.

Jost, K., Mayr, U., & Rosler, F. (2008). Is task switching nothing but cue priming? Evidence from ERPs. *Cognitive, Affective & Behavioral Neuroscience, 8*(1), 74-84.

Ju, Y. J., & Lien, Y. W. (2018). Who is prone to wander and when? Examining an integrative effect of working memory capacity and mindfulness trait on mind wandering under different task loads. *Consciousness and Cognition, 63*, 1-10.

Jurado, M. B., & Rosselli, M. (2007). The elusive nature of executive functions: A review of our current understanding. *Neuropsychology Review, 17*(3), 213-233.

Kane, M., Brown, L., McVay, J. C., Silvia, P. J., Myin-Germeys, I., & Kwapil, T. R. (2007). For whom the mind wanders, and when: An experience-sampling study of working memory and executive control in daily life. *Psychological Science, 18*(7), 614-621.

Kane, M., Poole, B. J., Tuholski, S. W., & Engle, R. W. (2003). *Working memory capacity and executive control in search and switching.* Paper presented at the Poster presented at the Annual Meeting of the Psychonomic Society, Vancouver, Canada.

Kane, M. J., Bleckley, M. K., Conway, A. R., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology. General, 130*(2), 169-183.

Kane, M. J., Conway, A. R. A., Hambrick, D. Z., & Engle, R. W. (2007). Variation in working memory capacity as variation in executive attention and control. In A. Conway, C. Jarrold, M. Kane, A. Miyake, & J. Towse (Eds.), *Variation in Working Memory* (pp. 21-48). Oxford: Oxford University Press.

Kane, M. J., & Engle, R. W. (2000). Working-memory capacity, proactive interference, and divided attention: limits on long-term memory retrieval. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 26*(2), 336-358.

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin & Review, 9*(4), 637-671.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology. General, 132*(1), 47-70.

Kane, M. J., Gross, G. M., Chun, C. A., Smeekens, B. A., Meier, M. E., Silvia, P. J., & Kwapil, T. R. (2017). For whom the mind wanders, and when, varies across laboratory and daily-life settings. *Psychological Science, 28*(9), 1271-1289.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology. General, 133*(2), 189-217.

Kane, M. J., & McVay, J. C. (2012). What mind wandering reveals about executive-control abilities and failures. *Current Directions in Psychological Science, 21*(5), 348-354.

Kane, M. J., Meier, M. E., Smeekens, B. A., Gross, G. M., Chun, C. A., Silvia, P. J., & Kwapil, T. R. (2016). Individual differences in the executive control of attention, memory, and thought, and their associations with schizotypy. *Journal of Experimental Psychology: General, 145*(8), 1017-1048.

Kane, M. J., Poole, B. J., Tuholski, S. W., & Engle, R. W. (2006). Working memory capacity and the top-down control of visual search: Exploring the boundaries of "executive attention". *Journal of Experimental Psychology. Learning, Memory, and Cognition, 32*(4), 749-777.

Karayanidis, F., Jamadar, S., Ruge, H., Phillips, N., Heathcote, A., & Forstmann, B. U. (2010). Advance preparation in task-switching: Converging evidence from behavioral, brain activation, and model-based approaches. *Frontiers in Psychology, 1*, 25.

Kessler, Y., & Meiran, N. (2010). The reaction-time task-rule congruency effect is not affected by working memory load: Further support for the activated long-term memory hypothesis. *Psychological Research, 74*(4), 388-399.

Keuleers, E., Lacey, P., Rastle, K., & Brysbaert, M. (2012). The British Lexicon Project: Lexical decision data for 28,730 monosyllabic and disyllabic English words. *Behavior Research Methods, 44*(1), 287-304.

Kieras, D. E., Meyer, D. E., Mueller, S., & Seymour, T. (1999). Insights into working memory from the perspective of the EPIC architecture for modeling skilled perceptual-motor and cognitive human performance. In A. Miyake, & P. Shah (Eds.), *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control* (pp. 183-223). New York: Cambridge University Press.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching - a review. *Psychological Bulletin, 136*(5), 849-874.

Kiesel, A., Wendt, M., & Peters, A. (2007). Task switching: On the origin of response congruency effects. *Psychological Research, 71*(2), 117-125.

Kim, C., Cilles, S. E., Johnson, N. F., & Gold, B. T. (2012). Domain general and domain preferential brain regions associated with different types of task switching: A meta-analysis. *Human Brain Mapping, 33*(1), 130-142.

Klauer, K. C., Schmitz, F., Teige-Mocigemba, S., & Voss, A. (2010). Understanding the role of executive control in the implicit association test: Why flexible people have small IAT effects. *Quarterly Journal of Experimental Psychology, 63*(3), 595-619.

Knapp, K., & Morton, J. B. (2013). Brain development and executive functioning. In R. E. Tremblay, M. Boivin, & R. D. Peters (Eds.), *Encyclopedia on Early Childhood Development.* (pp. 1-7).

Knapp, K., & Morton, J. B. (2017). Executive functioning: A developmental cognive neuroscience perspective. In M. J. Hoskyn, G. Larocci, & A. R. Young (Eds.), *Executive Functions in Children's Everyday Lives: A Handbook for Professionals in Applied Psychology*. New York: Oxford University Press.

Koch, I., Poljac, E., Muller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking-An integrative review of dual-task and task-switching research. *Psychological Bulletin*, *144*(6), 557-583.

Kondo, H., Morishita, M., Osaka, N., Osaka, M., Fukuyama, H., & Shibasaki, H. (2004). Functional roles of the cingulo-frontal network in performance on working memory. *Neuroimage, 21*(1), 2-14.

Kondo, H., Osaka, N., & Osaka, M. (2004). Cooperation of the anterior cingulate cortex and dorsolateral prefrontal cortex for attention shifting. *Neuroimage*, *23*(2), 670-679.

Konig, C. J., Buhner, M., & Murling, G. (2005). Working memory, fluid intelligence, and attention are predictors of multitasking performance, but polychronicity and extraversion are not. *Human performance, 18*(3), 243-266.

Kool, W., & Botvinick, M. (2014). A labor/leisure tradeoff in cognitive control. *Journal of Experimental Psychology: General, 143*(1), 131-141.

Kool, W., Shenhav, A., & Botvinick, M. (2017). Cognitive control as cost-benefit decision making. In T. Egner (Ed.), *The Wiley Handbook of Cognitive Control* (pp. 167-189). Oxford: John Wiley & Sons.

Körner, U., Röer, J. P., Buchner, A., & Bell, R. (2019). Time of presentation affects auditory distraction: Changing-state and deviant sounds disrupt similar working memory processes. *Quarterly Journal of Experimental Psychology, 72*(3), 457-471.

Krawietz, S. A., Tamplin, A. K., & Radvansky, G. A. (2012). Aging and mind wandering during text comprehension. *Psychology and Aging, 27*(4), 951-958.

Kray, J. (2006). Task-set switching under cue-based versus memory-based switching conditions in younger and older adults. *Brain Research, 1105*(1), 83-92.

Kray, J., & Eppinger, B. (2006). Effects of associative learning on age differences in task-set switching. *Acta Psychologica, 123*(3), 187-203.

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging, 15*(1), 126-147.

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences, 9*(2), 75-82.

Lavie, N. (2010). Attention, distraction, and cognitive control under load. *Current Directions in Psychological Science, 19*(3), 143-148.

Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology. General, 133*(3), 339-354.

Levinson, D. B., Smallwood, J., & Davidson, R. J. (2012). The persistence of thought: evidence for a role of working memory in the maintenance of task-unrelated thinking. *Psychological Science, 23*(4), 375-380.

Li, B., Li, X., Stoet, G., & Lages, M. (2019). Exploring individual differences in task switching. *Acta psychologica, 193,* 80-95.

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

Liefooghe, B., Wenke, D., & De Houwer, J. (2012). Instruction-based task-rule congruency effects. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 38*(5), 1325-1335.

Liu, S., Wadeson, A., Kim, N. Y., & Nam, C. S. (2016). Effects of working memory capacity, task switching, and task difficulty on multitasking performance. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 60*(1), 502-506.

Logan, G. D. (2004). Working memory, task switching, and executive control in the task span procedure. *Journal of Experimental Psychology. General, 133*(2), 218-236.

Logan, G. D., & Bundesen, C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task-cuing procedure? *Journal of Experimental Psychology. Human Perception and Performance, 29*(3), 575-599.

Logan, G. D., & Bundesen, C. (2004). Very clever homunculus: Compound stimulus strategies for the explicit task-cuing procedure. *Psychonomic Bulletin & Review, 11*(5), 832-840.

Logan, G. D., & Schneider, D. W. (2006). Interpreting instructional cues in task switching procedures: The role of mediator retrieval. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 32*(2), 347-363.

Logan, G. D., & Schneider, D. W. (2010). Distinguishing reconfiguration and compound-cue retrieval in task switching. *Psychologica Belgica, 50*(3), 413-433.

Logie, R. H., Law, A., Trawley, S., & Nissan, J. (2010). Multitasking, working memory and remembering intentions. *Psychologica Belgica*, *50*(3-4), 309-326.

Logue, S. F., & Gould, T. J. (2014). The neural and genetic basis of executive function: Attention, cognitive flexibility, and response inhibition. *Pharmacology, Biochemistry, and Behavior, 123*, 45-54.

Lovett, M. C., Daily, L. Z., & Reder, L. M. (2000). A source activation theory of working memory: Cross-task prediction of performance in ACT-R. *Cognitive Systems Research, 1*(2), 99-118.

Luo, X., Zhang, L., & Wang, J. (2017). The benefits of working memory capacity on attentional control under pressure. *Frontiers in Psychology, 8*, 1105.

MacDonald, S. W., Nyberg, L., & Bäckman, L. (2006). Intra-individual variability in behavior: Links to brain structure, neurotransmission and neuronal activity. *Trends in Beurosciences, 29*(8), 474-480.

Macken, W. J., Phelps, F. G., & Jones, D. M. (2009). What causes auditory distraction? *Psychonomic Bulletin & Review, 16*(1), 139-144.

Mayr, U. (2006). What matters in the cued task-switching paradigm: Tasks or cues? *Psychonomic Bulletin & Review, 13*(5), 794-799.

Mayr, U. (2010). The surface structure and the deep structure of sequential control: What can we learn from task span switch costs? *Psychonomic Bulletin & Review, 17*(5), 693-698.

Mayr, U., & Kliegl, R. (2000). Task-set switching and long-term memory retrieval. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 26*(5), 1124-1140.

Mayr, U., & Kliegl, R. (2003). Differential effects of cue changes and task changes on task-set selection costs. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 29*(3), 362-372.

McVay, J. C., & Kane, M. J. (2009a). Conducting the train of thought: working memory capacity, goal neglect, and mind wandering in an executive-control task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(1), 196-204.

McVay, J. C., & Kane, M. J. (2009b). Conducting the train of thought: Working memory capacity, goal neglect, and mind wandering in an executive-control task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(1), 196.

McVay, J. C., & Kane, M. J. (2010). Does mind wandering reflect executive function or executive failure? Comment on Smallwood and Schooler (2006) and Watkins (2008). *Psychological Bulletin, 136*(2), 188-207.

McVay, J. C., & Kane, M. J. (2012a). Drifting from slow to “d'oh!”: Working memory capacity and mind wandering predict extreme reaction times and executive control errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(3), 525-549.

McVay, J. C., & Kane, M. J. (2012b). Why does working memory capacity predict variation in reading comprehension? On the influence of mind wandering and executive attention. *Journal of Experimental Psychology. General, 141*(2), 302-320.

Meier, M. E., & Kane, M. (2017). Attentional control and working memory capacity. In T. Egner (Ed.), *The Wiley Handbook of Cognitive Control* (pp. 50-63). Oxford: John Wiley & Sons.

Meier, M. E., Smeekens, B. A., Silvia, P. J., Kwapil, T. R., & Kane, M. J. (2018). Working memory capacity and the antisaccade task: A microanalytic-macroanalytic investigation of individual differences in goal activation and maintenance. *J Exp Psychol Learn Mem Cogn, 44*(1), 68-84.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*(6), 1423-1442.

Meiran, N. (2014). The task-cuing paradigm: A user's guide. In J. A. Grange, & G. Houghton (Eds.), *Task Switching and Cognitive Control* (pp. 45-73). Oxford: Oxford University Press.

Meiran, N., Chorev, Z., & Sapir, A. (2000). Component processes in task switching. *Cognitive Psychology, 41*(3), 211-253.

Meiran, N., & Kessler, Y. (2008). The task rule congruency effect in task switching reflects activated long-term memory. *Journal of Experimental Psychology. Human Perception and Performance, 34*(1), 137-157.

Miller, A. L., & Unsworth, N. (2018). Individual differences in working memory capacity and search efficiency. *Memory & Cognition, 46*(7), 1149-1163.

Miller, J., & Ulrich, R. (2013). Mental chronometry and individual differences: Modeling reliabilities and correlations of reaction time means and effect sizes. *Psychonomic Bulletin & Review, 20*(5), 819-858.

Mittelstadt, V., Miller, J., & Kiesel, A. (2018). Trading off switch costs and stimulus availability benefits: An investigation of voluntary task-switching behavior in a predictable dynamic multitasking environment. *Memory & Cognition, 46*(5), 699-715.

Miyake, A., Emerson, M. J., Padilla, F., & Ahn, J. C. (2004). Inner speech as a retrieval aid for task goals: The effects of cue type and articulatory suppression in the random task cuing paradigm. *Acta Psychologica, 115*(2), 123-142.

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science, 21*(1), 8-14.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49-100.

Miyake, A., & Shah, P. (1999). *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*. Cambridge: Cambridge University Press.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences, 7*(3), 134-140.

Monsell, S. (2017). Task set regulation. In T. Egner (Ed.), *The Wiley Handbook of Cognitive Control* (pp. 29-49). Oxford: John Wiley & Sons.

Monsell, S., & Mizon, G. A. (2006). Can the task-cuing paradigm measure an endogenous task-set reconfiguration process? *Journal of Experimental Psychology. Human Perception and Performance, 32*(3), 493-516.

Monsell, S., Sumner, P., & Waters, H. (2003). Task-set reconfiguration with predictable and unpredictable task switches. *Memory & Cognition, 31*(3), 327-342.

Niendam, T. A., Laird, A. R., Ray, K. L., Dean, Y. M., Glahn, D. C., & Carter, C. S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cognitive, Affective & Behavioral Neuroscience, 12*(2), 241-268.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self regulation: Advances in research, Vol. IV* (pp. 1-18). New York: Plenum Press.

Nunnally, J. C. (1978). *Psychometric Theory*. New York: McGraw-Hill Book Company.

Oberauer, K. (2009). Design for a working memory. *The Psychology of Learning and Motivation, 51*, 45-100.

Oberauer, K., Lewandowsky, S., Awh, E., Brown, G. D. A., Conway, A., Cowan, N., . . . Ward, G. (2018). Benchmarks for models of short-term and working memory. *Psychological Bulletin, 144*(9), 885-958.

Oberauer, K., Süß, H.-M., Wilhelm, O., & Wittman, W. W. (2003). The multiple faces of working memory: Storage, processing, supervision, and coordination. *Intelligence, 31*(2), 167-193.

Oberauer, K., Suss, H. M., Wilhelm, O., & Sander, N. (2007). Individual differences in working memory capacity and reasoning ability. In A. Conway, C. Jarrold, M. Kane, A. Miyake, & J. Towse (Eds.), *Variation in Working Memory* (pp. 49-75). Oxford: Oxford University Press.

Osaka, M., & Osaka, N. (2007). Neural bases of focusing attention in working memory: An fMRI study based on individual differences. In N. Osaka, R. H. Logie, & M. D'Esposito (Eds.), *The Cognitive Neuroscience of Working Memory* (pp. 99-118). Oxford: Oxford University Press.

Osaka, M., Osaka, N., Kondo, H., Morishita, M., Fukuyama, H., Aso, T., & Shibasaki, H. (2003). The neural basis of individual differences in working memory capacity: An fMRI study. *Neuroimage, 18*(3), 789-797.

Osaka, N., Osaka, M., Kondo, H., Morishita, M., Fukuyama, H., & Shibasaki, H. (2004). The neural basis of executive function in working memory: An fMRI study based on individual differences. *Neuroimage, 21*(2), 623-631.

Osborne, J. W., & Overbay, A. (2004). The power of outliers (and why researchers should always check for them). *Practical Assessment, Research & Evaluation, 9*(6), 1-12.

Paap, K. R., & Sawi, O. (2016). The role of test-retest reliability in measuring individual and group differences in executive functioning. *Journal of Neuroscience Methods, 274*, 81-93.

Parsons, S., Kruijt, A.-W., & Fox, E. (2019). *Psychological Science needs a standard practice of reporting the reliability of cognitive behavioural measurements*. Manuscript submitted for publication.

Peirce, J. W. (2007). PsychoPy—psychophysics software in Python. *Journal of Neuroscience Methods, 162*(1), 8-13.

Peters, M., Giesbrecht, T., Jelicic, M., & Merckelbach, H. (2007). The random number generation task: Psychometric properties and normative data of an executive function task in a mixed sample. *Journal of the International Neuropsychological Society, 13*(4), 626-634.

Pettigrew, C., & Martin, R. C. (2016). The role of working memory capacity and interference resolution mechanisms in task switching. *Quarterly Journal of Experimental Psychology, 69*(12), 2431-2451.

Pollard, M. A., & Courage, M. L. (2017). Working memory capacity predicts effective multitasking. *Computers in Human Behavior, 76,* 450-462.

Poole, B. J., & Kane, M. J. (2009). Working-memory capacity predicts the executive control of visual search among distractors: The influences of sustained and selective attention. *The Quarterly Journal of Experimental Psychology, 62*(7), 1430-1454.

Psychology Software Tools Inc. (2012). E-Prime (Version 2.0). Retrieved from http://www.pstnet.com

Randall, J. G., Oswald, F. L., & Beier, M. E. (2014). Mind-wandering, cognition, and performance: A theory-driven meta-analysis of attention regulation. *Psychological Bulletin, 140*(6), 1411-1431.

Redick, T. S. (2016). On the relation of working memory and multitasking: Memory span and synthetic work performance. *Journal of Applied Research in Memory and Cognition, 5*(4), 401-409.

Redick, T. S., Broadway, J. M., Meier, M. E., Kuriakose, P. S., Unsworth, N., Kane, M., & Engle, R. W. (2012). Measuring working memory capacity with automated complex span tasks. *European Journal of Psychological Assessment, 28*(3), 164-171.

Redick, T. S., & Lindsey, D. R. (2013). Complex span and n-back measures of working memory: A meta-analysis. *Psychonomic Bulletin & Review, 20*(6), 1102-1113.

Redick, T. S., Shipstead, Z., Meier, M. E., Montroy, J. J., Hicks, K. L., Unsworth, N., . . . Engle, R. W. (2016). Cognitive predictors of a common multitasking ability: Contributions from working memory, attention control, and fluid intelligence. *Journal of Experimental Psychology: General, 145*(11), 1473-1492.

Revelle, W., Wilt, J., & Allen, T. (2010). Individual differences in cognition: New methods for examining the personality-cognition link. In A. Gruszka, G. Matthews, & B. Szymura (Eds.), *Handbook of Individual Differences in Cognition: Attention, Memory, and Executive Control* (pp. 27-49). New York: Springer.

Richter, F. R., & Yeung, N. (2014). Neuroimaging studies of task switching. In J. A. Grange, & G. Houghton (Eds.), *Task Switching and Cognitive Control* (pp. 237-271). Oxford: Oxford University Press.

Robison, M. K., Miller, A. L., & Unsworth, N. (2018). Individual differences in working memory capacity and filtering. *Journal of Experimental Psychology: Human Perception and Performance, 44*(7), 1038-1053.

Robison, M. K., & Unsworth, N. (2018). Cognitive and contextual correlates of spontaneous and deliberate mind-wandering. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 44*(1), 85-98.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictible switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*(2), 207-231.

Rosen, V. M., & Engle, R. W. (1997). The role of working memory capacity in retrieval. *Journal of Experimental Psychology: General, 126*(3), 211-227.

Rouder, J., Kumar, A., & Haaf, J. M. (2019). *Why most studies of individual differences with inhibition tasks are bound to fail*. Manuscript submitted for publication.

Ruge, H., Jamadar, S., Zimmermann, U., & Karayanidis, F. (2013). The many faces of preparatory control in task switching: Reviewing a decade of fMRI research. *Human Brain Mapping, 34*(1), 12-35.

Rummel, J., & Boywitt, C. D. (2014). Controlling the stream of thought: Working memory capacity predicts adjustment of mind-wandering to situational demands. *Psychonomic Bulletin & Review, 21*(5), 1309-1315.

Saeki, E., & Saito, S. (2004). Effect of articulatory suppression on task-switching performance: Implications for models of working memory. *Memory, 12*(3), 257-271.

Saeki, E., & Saito, S. (2012). Differential effects of articulatory suppression on cue-switch and task-switch trials in random task cueing with 2:1 mapping. *The Quarterly Jounal of Experimental Psychology, 65*(8), 1599-1614.

Salame, P., & Baddeley, A. (1982). Disruption of short-term memory by unattended speech: Implications for the structure of working memory. *Journal of Memory and Language, 21*(2), 150-164.

Salthouse, T. A., Fristoe, N., McGuthry, K. E., & Hambrick, D. Z. (1998). Relation of task switching to speed, age, and fluid intelligence. *Psychology and aging, 13*(3), 445-461.

Schmidt, J. R., & Liefooghe, B. (2016). Feature integration and task switching: Diminished switch costs after controlling for stimulus, response, and cue Repetitions. *PLoS One, 11*(3), e0151188.

Schmitz, F., Teige-Mocigemba, S., Voss, A., & Klauer, K. C. (2013). When scoring algorithms matter: Effects of working memory load on different IAT scores. *The British Journal of Social Psychology, 52*(1), 103-121.

Schmitz, F., & Voss, A. (2014). Components of task switching: A closer look at task switching and cue switching. *Acta Psychologica, 151*, 184-196.

Schneider, D. W., & Logan, G. D. (2005). Modeling task switching without switching tasks: A short-term priming account of explicitly cued performance. *Journal of Experimental Psychology. General, 134*(3), 343-367.

Schneider, D. W., & Logan, G. D. (2006). Priming cue encoding by manipulating transition frequency in explicitly cued task switching. *Psychonomic Bulletin & Review, 13*(1), 145-151.

Schneider, D. W., & Logan, G. D. (2010). The target of task switching. *Canadian Journal of Experimental Psychology, 64*(2), 129-133.

Schneider, D. W., & Logan, G. D. (2011). Task-switching performance with 1:1 and 2:1 cue-task mappings: Not so different after all. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 37*(2), 405-415.

Schweizer, K. (2010). The relationship of attention and intelligence. In A. Gruszka, G. Matthews, & B. Szymura (Eds.)*, Handbook of Individual Differences in Cognition: Attention, Memory, and Executive Control* (pp. 247-262). New York: Springer.

Seli, P., Cheyne, J. A., Xu, M., Purdon, C., & Smilek, D. (2015). Motivation, intentionality, and mind wandering: Implications for assessments of task-unrelated thought. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*(5), 1417-1425.

Seli, P., Kane, M. J., Smallwood, J., Schacter, D. L., Maillet, D., Schooler, J. W., & Smilek, D. (2018). Mind-wandering as a natural kind: A family-resemblances view. *Trends in Cognitive Sciences, 22*(6), 479-490.

Sexton, N. J., & Cooper, R. P. (2014). An architecturally constrained model of random number generation and its application to modeling the effect of generation rate. *Frontiers in Psychology, 5*, 670.

Shenhav, A., Botvinick, M. M., & Cohen, J. D. (2013). The expected value of control: an integrative theory of anterior cingulate cortex function. *Neuron, 79*(2), 217-240.

Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin, 132*(6), 946-958.

Smallwood, J., & Schooler, J. W. (2015). The science of mind wandering: Empirically navigating the stream of consciousness. *Annual Review of Psychology, 66*, 487-518.

Sohn, M. H., & Anderson, J. R. (2001). Task preparation and task repetition: Two-component model of task switching. *Journal of Experimental Psychology. General, 130*(4), 764-778.

Sörqvist, P. (2010). Effects of aircraft noise and speech on prose memory: What role for working memory capacity? *Journal of Environmental Psychology, 30*(1), 112-118.

Sörqvist, P., Halin, N., & Hygge, S. (2010). Individual differences in susceptibility to the effects of speech on reading comprehension. *Applied Cognitive Psychology, 24*(1), 67-76.

Sörqvist, P., Marsh, J. E., & Nöstl, A. (2013). High working memory capacity does not always attenuate distraction: Bayesian evidence in support of the null hypothesis. *Psychonomic Bulletin & Review, 20*(5), 897-904.

Sörqvist, P., & Rönnberg, J. (2014). Individual differences in distractibility: An update and a model. *PsyCh Journal, 3*(1), 42-57.

Souza, A. S., Oberauer, K., Gade, M., & Druey, M. D. (2012). Processing of representations in declarative and procedural working memory. *Quarterly Journal of Experimental Psychology 65*(5), 1006-1033.

Spearman, C. (1925). Some issues in the theory of “g”(including the law of diminishing returns). *116,* 436-439.

Spector, A., & Biederman, I. (1976). Mental set and mental shift revisited. *The American Journal of Psychology, 89*(4), 669-679.

Strobach, T., Wendt, M., & Janczyk, M. (2018). Editorial: Multitasking: Executive functioning in dual-task and task switching situations. *Fronteirs in Psychology, 9*, 108.

Towse, J., & Hitch, G. (1995). Is there a relationship between task demand and storage space in tests of working memory capacity? *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology, 48*(1), 108-124.

Towse, J., & Hitch, G. (2007). Variation in working memory due to normal development. In A. R. Conway, C. Jarrold, M. Kane, A. Miyake, & J. Towse (Eds.), *Variation in Working Memory* (pp. 109-133). Oxford: Oxford University Press.

Towse, J. N., Hitch, G. J., & Hutton, U. (2000). On the interpretation of working memory span in adults. *Memory & Cognition, 28*(3), 341-348.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language, 28*(2), 127-154.

Underwood, B. J. (1975). Individual differences as a crucible in theory construction. *American Psychologist, 30*(2), 128-134.

Unsworth, N. (2015). Consistency of attentional control as an important cognitive trait: A latent variable analysis. *Intelligence, 49,* 110-128.

Unsworth, N., & Engle, R. W. (2008). Speed and accuracy of accessing information in working memory: An individual differences investigation of focus switching.

Journal of Experimental Psychology. Learning, Memory, and Cognition, 34(3), 616-630.

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods, 37*(3), 498-505.

Unsworth, N., & McMillan, B. D. (2014). Similarities and differences between mind-wandering and external distraction: A latent variable analysis of lapses of attention and their relation to cognitive abilities. *Acta Psychologica, 150*, 14-25.

Unsworth, N., Redick, T. S., Heitz, R. P., Broadway, J. M., & Engle, R. W. (2009). Complex working memory span tasks and higher-order cognition: A latent-variable analysis of the relationship between processing and storage. *Memory, 17*(6), 635-654.

Unsworth, N., Redick, T. S., Spillers, G. J., & Brewer, G. A. (2012). Variation in working memory capacity and cognitive control: Goal maintenance and microadjustments of control. *Quarterly Journal of Experimental Psychology, 65*(2), 326-355.

Unsworth, N., & Robison, M. K. (2016). The influence of lapses of attention on working memory capacity. *Memory & Cognition, 44*(2), 188-196.

van der Wel, P., & van Steenbergen, H. (2018). Pupil dilation as an index of effort in cognitive control tasks: A review. *Psychonomic Bulletin & Review, 25*(6), 2005-2015.

Vandierendonck, A. (2012). Role of working memory in task switching. *Psychologica Belgica, 52*(2), 229-253.

Vandierendonck, A. (2016). A working memory system with distributed executive control. *Perspectives on Psychological Science, 11*(1), 74-100.

Vandierendonck, A. (2018). Working memory benchmarks—A missed opportunity: Comment on Oberauer et al (2018). *Psychological Bulletin, 144*(9), 963-971.

Vandierendonck, A., Liefooghe, B., & Verbruggen, F. (2010). Task switching: Interplay of reconfiguration and interference control. *Psychological Bulletin, 136*(4), 601-626.

Vogel, E. K., & Awh, E. (2008). How to exploit diversity for scientific gain: Using individual differences to constrain cognitive theory. *Current Directions in Psychological Science, 17*(2), 171-176.

von Bastian, C. C., & Druey, M. D. (2017). Shifting between mental sets: An individual differences approach to commonalities and differences of task switching components. *Journal of Experimental Psychology. General, 146*(9), 1266-1285.

Wager, T. D., Jonides, J., & Reading, S. (2004). Neuroimaging studies of shifting attention: A meta-analysis. *Neuroimage, 22*(4), 1679-1693.

Wais, P. E., & Gazzaley, A. (2011). The impact of auditory distraction on retrieval of visual memories. *Psychonomic Bulletin & Review, 18*(6), 1090-1097.

Weinstein, Y. (2018). Mind-wandering, how do I measure thee with probes? Let me count the ways. *Behavior Research Methods, 50*, 642-661.

Weywadt, C. R., & Butler, K. M. (2013). The role of verbal short-term memory in task selection: How articulatory suppression influences task choice in voluntary task switching. *Psychonomic Bulletin & Review, 20*(2), 334-340.

Wierzchoń, M., Gaillard, V., Asanowicz, D., & Cleeremans, A. (2012). Manipulating attentional load in sequence learning through random number generation. *Advances in Cognitive Psychology, 8*(2), 179-195.

Yarkoni, T., & Braver, T. S. (2010). Cognitive neuroscience approaches to individual differences in working memory and executive control: Conceptual and methodological issues. In A. Gruszka, G. Matthews, & B. Szymura (Eds.), *Handbook of Individual Differences in Cognition: Attention, Memory, and Executive Control* (pp. 87-107). New York: Springer.

Ziegler, D. A., Janowich, J. R., & Gazzaley, A. (2018). Differential impact of interference on internally and externally directed attention. *Scientific Reports, 8*(1), 2498.

Appendix A

Supplementary Results from Experiment 1

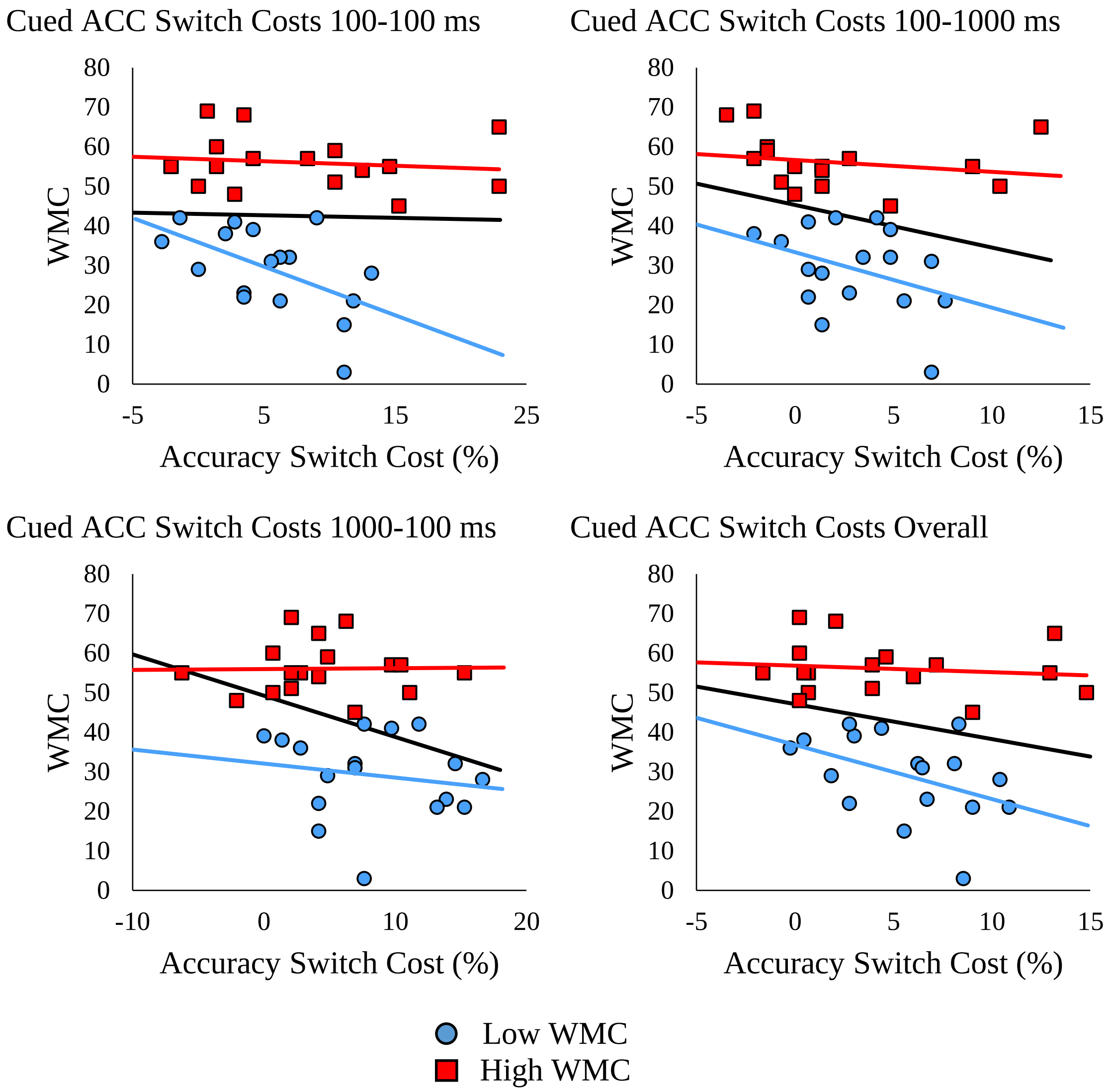
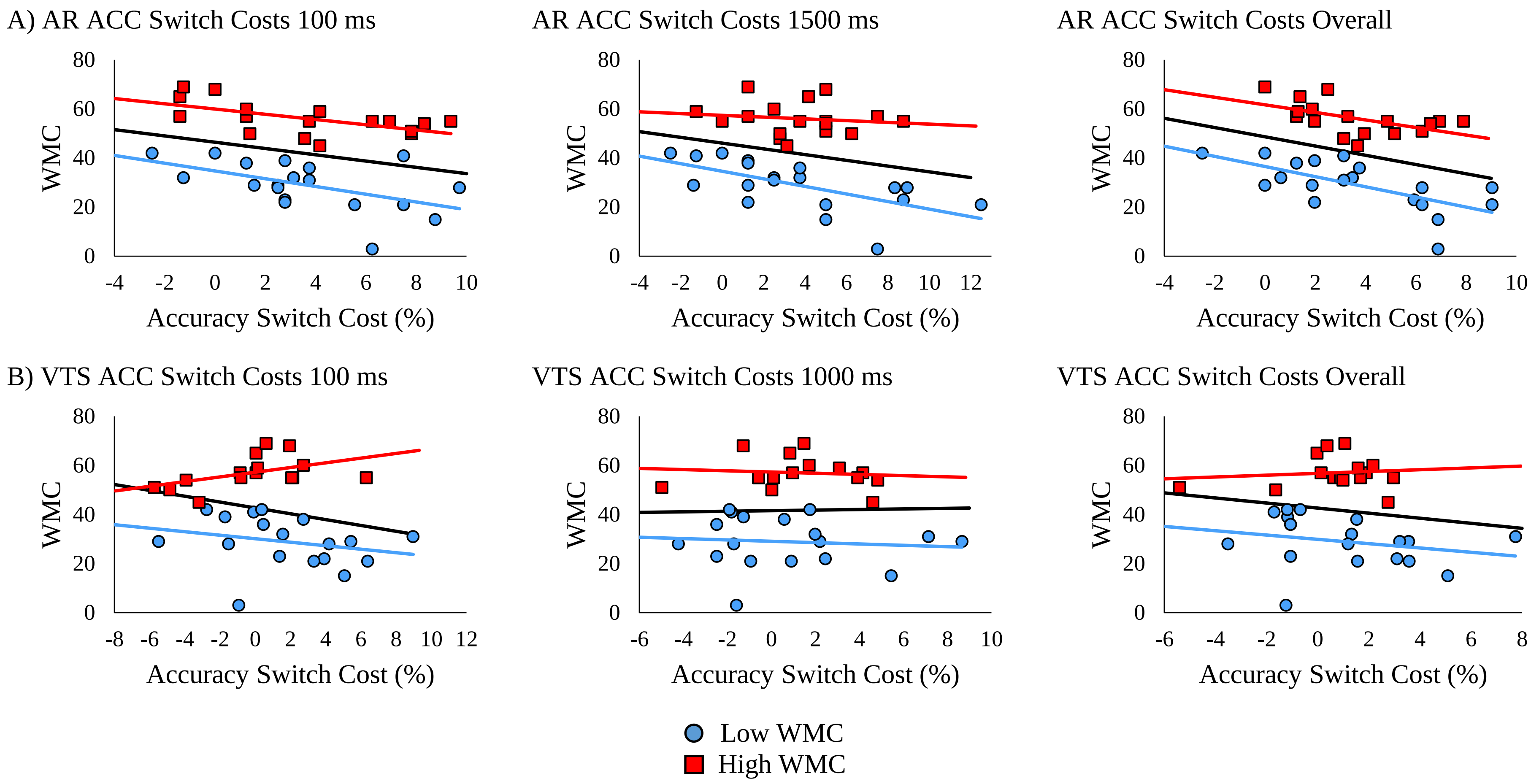


Figure A-1. Scatterplots of the relationship between working memory capacity (WMC) and accuracy (ACC) switch costs in low and high WMC participants on the explicitly cued task switching paradigm. These relationships are shown overall and across the three timing manipulations. The centre line indicates the regression line for the full sample.



A) AR ACC Switch Costs 100 ms

AR ACC Switch Costs 1500 ms

AR ACC Switch Costs Overall

B) VTS ACC Switch Costs 100 ms

VTS ACC Switch Costs 1000 ms

VTS ACC Switch Costs Overall

Figure A-2. Scatterplots of the relationship between working memory capacity (WMC) and accuracy (ACC) switch costs in high and low WMC participants on the A) alternating runs (AR) and B) voluntary task switching (VTS) paradigms. These relationships are shown overall and across the two timing manipulations used in these switching paradigms. The centre line indicates the regression line for the full sample.

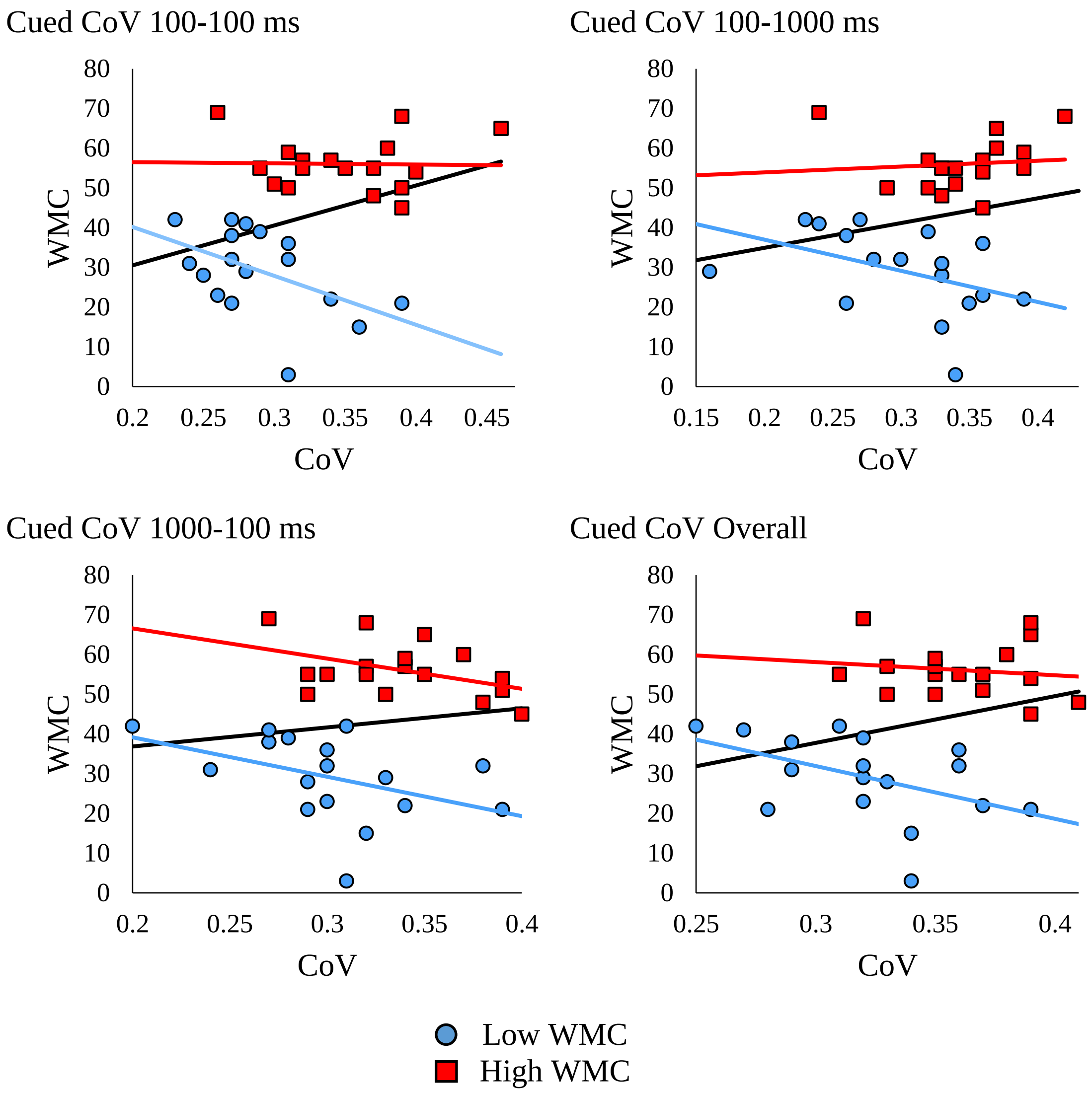


Figure A-3. Scatterplots of the relationship between working memory capacity (WMC) and the coefficient of variation (CoV) in high and low WMC participants on the explicitly cued task switching paradigm. These relationships are shown overall and across the three timing manipulations. The centre line indicates the regression line for the full sample.

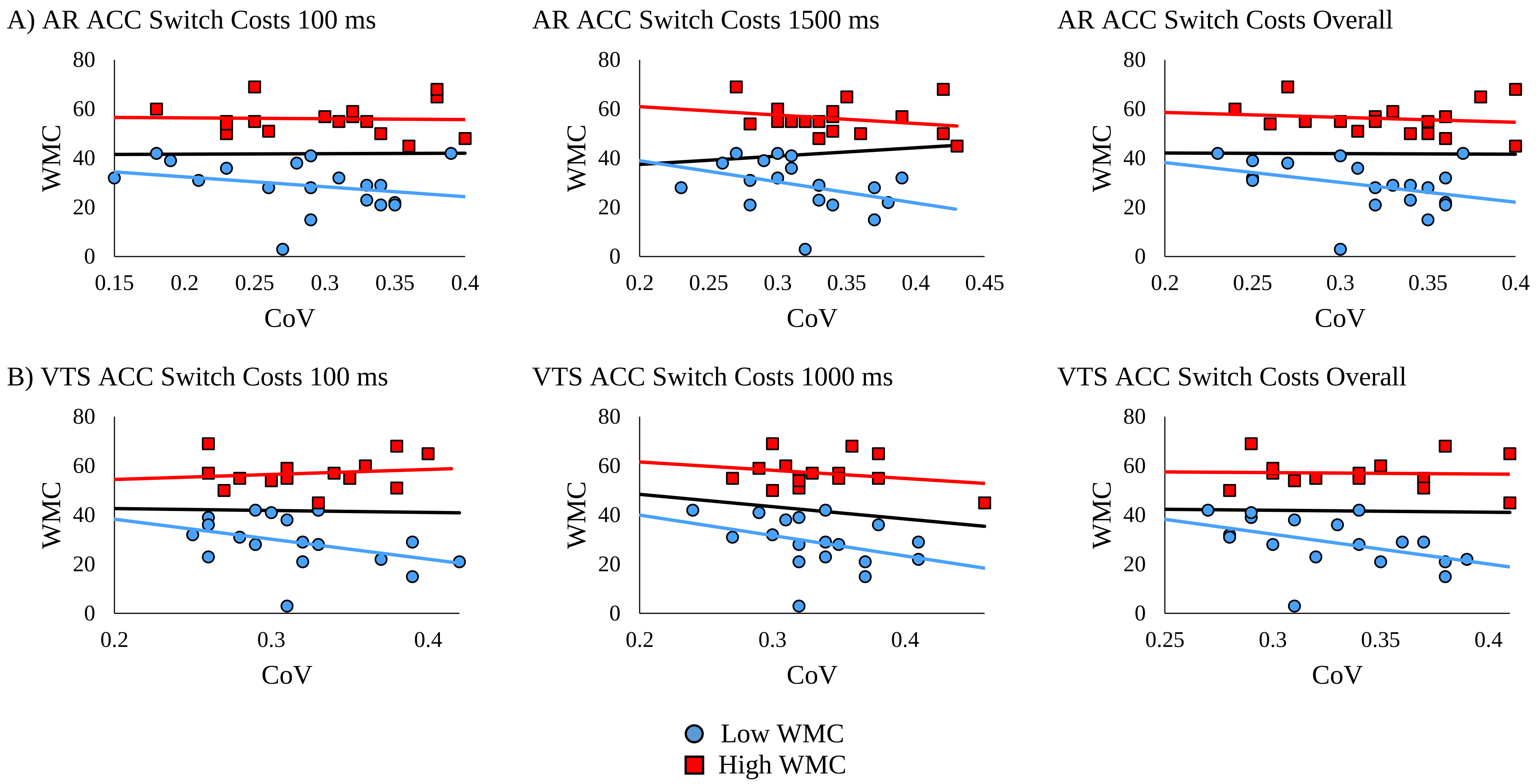
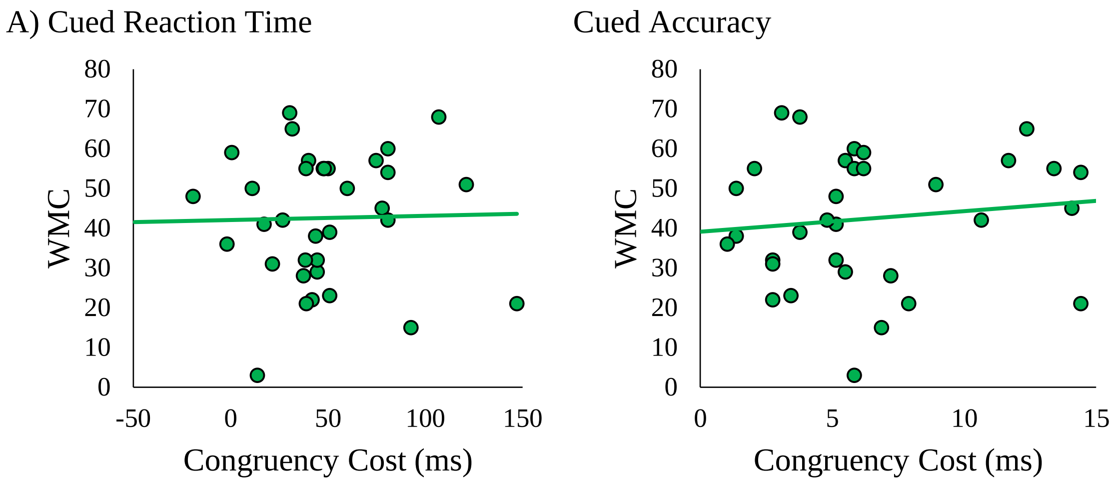


Figure A-4. Scatterplots of the relationship between working memory capacity (WMC) and the coefficient of variation (CoV) in high and low WMC participants on the A) alternating runs (AR) and B) voluntary task switching (VTS) paradigms. These relationships are shown overall and in the two timing manipulations in these switching paradigms. The centre line indicates the regression line for the full sample.



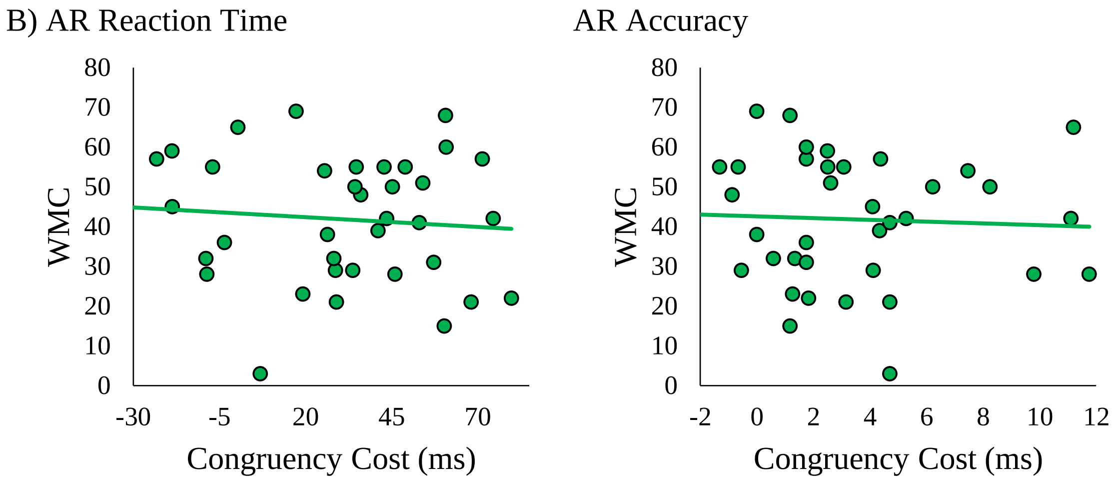


Figure A-5. Scatterplots of the relationship between working memory capacity (WMC) and reaction time and accuracy congruency costs. This is shown for both A) the explicitly cued task switching paradigm and B) the AR paradigm.

Appendix B

Task Difficulty Questionnaire

Instructions: Please respond to the statements below describing your feelings about the switching task you have just completed. Circle one response (one number) under each item.

How **difficult** did you find the switching task alone?

Very easy Very difficult
1 —— 2 —— 3 —— 4 —— 5 —— 6 —— 7

How **difficult** did you find the switching task when it was completed with the auditory distraction task?

Very easy Very difficult
1 —— 2 —— 3 —— 4 —— 5 —— 6 —— 7

How **difficult** did you find the working memory task that you completed initially?

Very easy Very difficult
1 —— 2 —— 3 —— 4 —— 5 —— 6 —— 7

Appendix C

Supplementary Results from Experiment 2

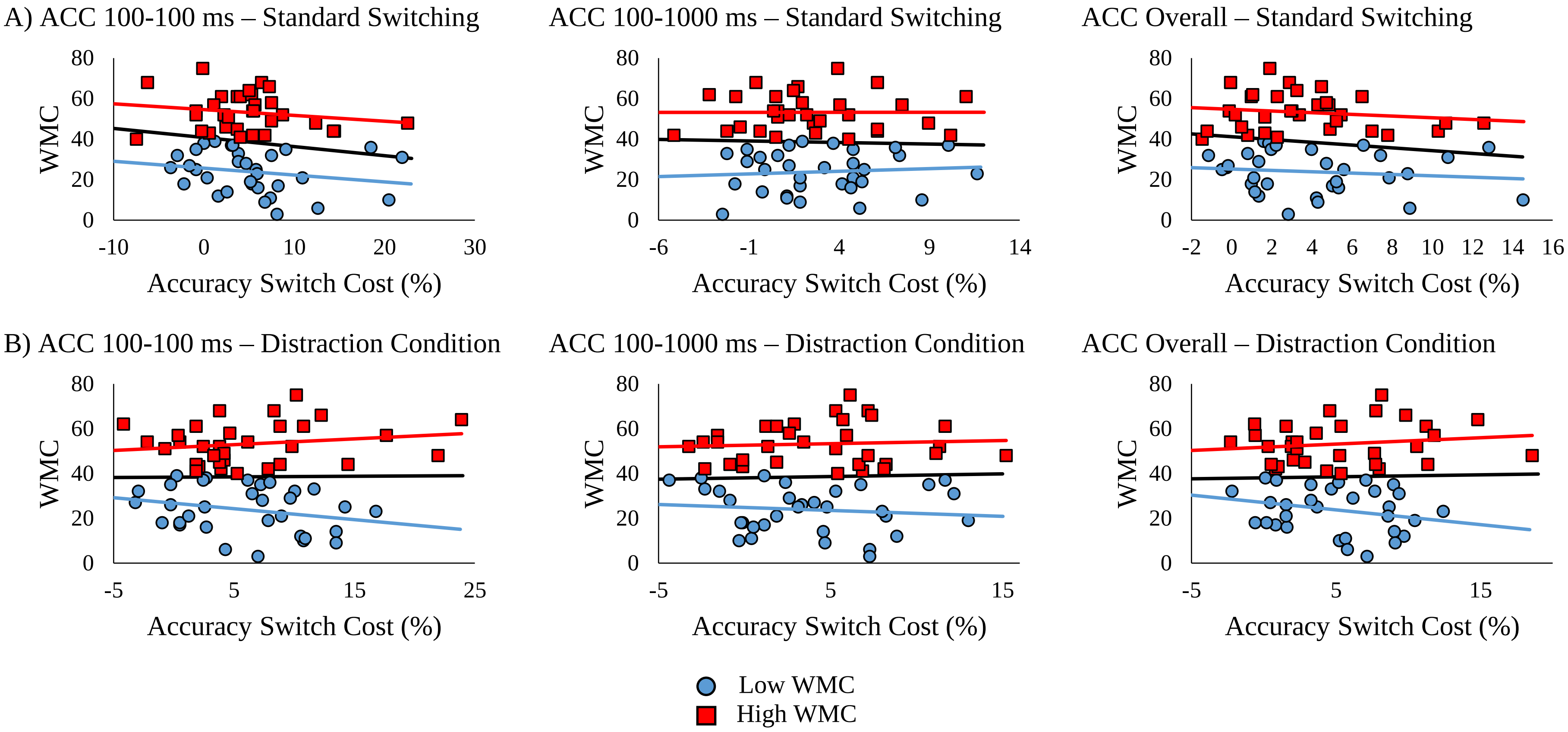


Figure C-1. Scatterplots of the relationship between working memory capacity (WMC) and accuracy (ACC) switch costs on the standard switching paradigm, and B) during the auditory distraction version for low and high WMC. These relationships are shown overall and across the two timing manipulations used in the switching paradigm. The centre line indicates the regression line for the full sample.

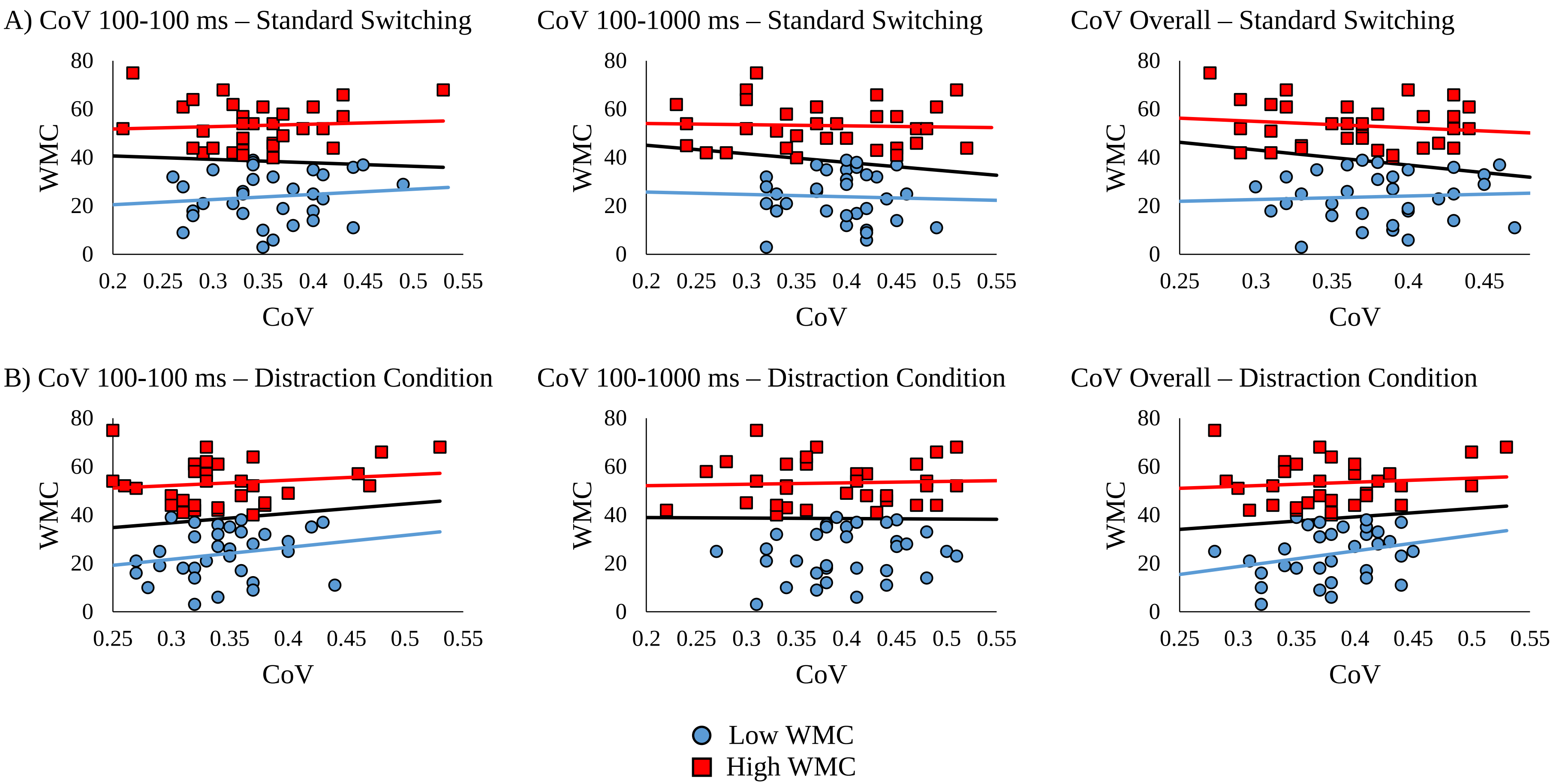


Figure C-2. Scatterplots of the relationship between A) working memory capacity (WMC) and the coefficient of variation (CoV) during the standard switching paradigm, and B) during the auditory distraction version for low and high WMC. These relationships are shown overall and in the two timing manipulations used in the paradigm. The centre line indicates the regression line for the full sample.

Appendix D

Supplementary Results from Experiment 3

All analyses were completed both with outliers included and with outliers excluded. Below you will find each of the analyses included in the main text of this chapter alongside their counterpart with outliers excluded. Table D-1a and D-1b display the descriptive statistics and correlations between WMC and task switch costs. Table D-1a is identical to Table 7 in the main text of Chapter 4 as it displays the analyses with outliers included. Table D-1b shows the same analyses but with outliers removed. One line of these tables is bold and italicized. This displays the only analysis which provided a different result when outliers were removed.

Table D-2a and D-2b display the descriptive statistics and correlations between WMC and cue switch costs. Table D-2a is identical to Table 8 in the main text of Chapter 4 and includes all outliers. Table D-2b shows the same analyses with outliers removed, which led to no major changes. The coefficient of variation (CoV) analyses did not include any outliers. RT and ACC congruency cost analyses were also re-done with outliers excluded. See table D-3a for a summary of the congruency cost results with outliers included and table D-3b for results with outliers excluded. Excluding outliers did not make changes to any conclusions.

Table D-1a

Descriptive Statistics, Reliabilities, and Correlations with WMC for Task Switch Costs and Bin Scores with Outliers Included

Measure	*M*	*SD*	α	WMC *r*	*p*	*N*
Task Switch Cost ACC (Repeat – Switch (%))						
Overall	70	34	.58	-.09	.39	102
1000-100	***101***	***51***	***.58***	***-.15***	***.14***	***102***
100-1000	40	34	.30	.04	.72	102
Task Switch Cost ACC (Repeat – Switch (%))						
Overall	4.4	3.0	.44	-.14	.17	102
1000-100	6.2	4.5	.42	-.13	.20	102
100-1000	2.6	3.2	.23	-.08	.43	102
Task Switch Bin Score						
Overall	1306	140	.70	-.17	.09	102
1000-100	689	95	.69	-.25*	.01	102
100-1000	617	72	.54	-.01	.93	102

Note. WMC: working memory capacity; RT: reaction time; ACC: accuracy. Overall Cronbach's alpha reliabilities were calculated across all 8 blocks of the experiment. In each of the timing manipulations, reliabilities were calculated across the 4 blocks of the experiment that involved that timing manipulation. All tests are 2-tailed. * $p < .05$. For ACC switch costs, the Switch cost 100-1000 ms variable violated normality, so Spearman's rho was also calculated; $\rho(100) = -.11$, $p = .28$.

Table D-1b

Descriptive Statistics, Reliabilities, and Correlations with WMC for Task Switch Costs and Bin Scores with Outliers Excluded

Measure	*M*	*SD*	α	WMC *r*	*p*	*N*
Task Switch Cost RT (Switch – Repeat (ms))						
Overall	65	30	.46	-.14	.15	100
1000-100	***97***	***44***	***.43***	***-.23****	***.02***	***100***
100-1000	40	32	.18	-.06	.57	100
Task Switch Cost ACC (Repeat – Switch (%))						
Overall	4.4	2.8	.35	-.13	.20	100
1000-100	6.0	4.1	.31	-.11	.26	100
100-1000	2.6	3.2	.23	-.08	.43	102
Bin Scores						
Overall	1302	135	.67	-.17	.09	101
1000-100	689	95	.69	-.25*	.01	102
100-1000	615	69	.52	.02	.88	101

Note. WMC: working memory capacity; RT: reaction time; ACC: accuracy. Overall Cronbach's alpha reliabilities were calculated across all 8 blocks of the experiment. In each of the timing manipulations, reliabilities were calculated across the 4 blocks of the experiment that involved that timing manipulation. All tests are 2-tailed. * $p < .05$. For ACC switch costs, the Switch cost 100-1000 ms variable violated normality, so Spearman's rho was also calculated; $\rho(100) = -.11$, $p = .28$.

Table D-2a

Descriptive Statistics, Reliabilities, and Correlations with WMC for Cue Switch Costs and Bin Scores with Outliers Included

Measure	*M*	*SD*	α	WMC *r*	*p*	*N*
Cue Switch Cost RT (Switch – Repeat (ms))						
Overall	29	24	.37	-.07	.51	102
1000-100	43	34	.35	-.11	.28	102
100-1000	16	29	.32	.01	.91	102
Cue Switch Cost ACC (Repeat – Switch (%))						
Overall	-0.4	2.2	.18	.09	.38	102
1000-100	-0.5	2.9	-	.06	.58	102
100-1000	-0.3	2.7	.35	.08	.44	102
Cue Bin Scores						
Overall	2360	193	.58	-.10	.33	102
1000-100	1205	122	.54	-.17	.08	102
100-1000	1160	132	.63	.05	.65	102

Note. WMC: working memory capacity; RT: reaction time; ACC: accuracy. Overall Cronbach's alpha reliabilities were calculated across all 8 blocks of the experiment. In each of the timing manipulations, reliabilities were calculated across the 4 blocks of the experiment that involved that timing manipulation. All tests are 2-tailed. * p < .05. For variables that violated normality, Spearman's rho was also calculated: ACC cue switch costs overall: ρ(100) = .08, p = .43; ACC cue switch costs 1000-100 ms: ρ(100) = .08, p = .45; Cue bin scores overall: ρ(100) = -.10, p = .33. -: α was negative.

Table D-2b

Descriptive Statistics, Reliabilities, and Correlations with WMC for Cue Switch Costs and Bin Scores with Outliers Excluded

Measure	*M*	*SD*	α	WMC *r*	*p*	*N*
Cue Switch Cost RT (Switch – Repeat (ms))						
Overall	29	23	.31	-.07	.48	101
1000-100	42	32	.30	-.12	.25	101
100-1000	16	29	.32	.01	.91	102
Cue Switch Cost ACC (Repeat – Switch (%))						
Overall	-0.3	2.0	.14	.05	.60	100
1000-100	-0.4	2.5	-	.04	.67	99
100-1000	-0.2	2.4	.25	.08	.45	98
Cue Bin Scores						
Overall	2360	193	.58	-.10	.33	102
1000-100	1205	122	.54	-.17	.08	102
100-1000	1160	132	.63	.05	.65	102

Note. WMC: working memory capacity; RT: reaction time; ACC: accuracy. Overall Cronbach's alpha reliabilities were calculated across all 8 blocks of the experiment. In each of the timing manipulations, reliabilities were calculated across the 4 blocks of the experiment that involved that timing manipulation. All tests are 2-tailed. * *p* < .05. For variables that violated normality, Spearman's rho was also calculated: ACC cue switch costs overall: *ρ*(98) = .08, *p* = .43; Cue bin scores overall: *ρ*(100) = -.10, *p* = .33. -: α was negative.

Table D-3a

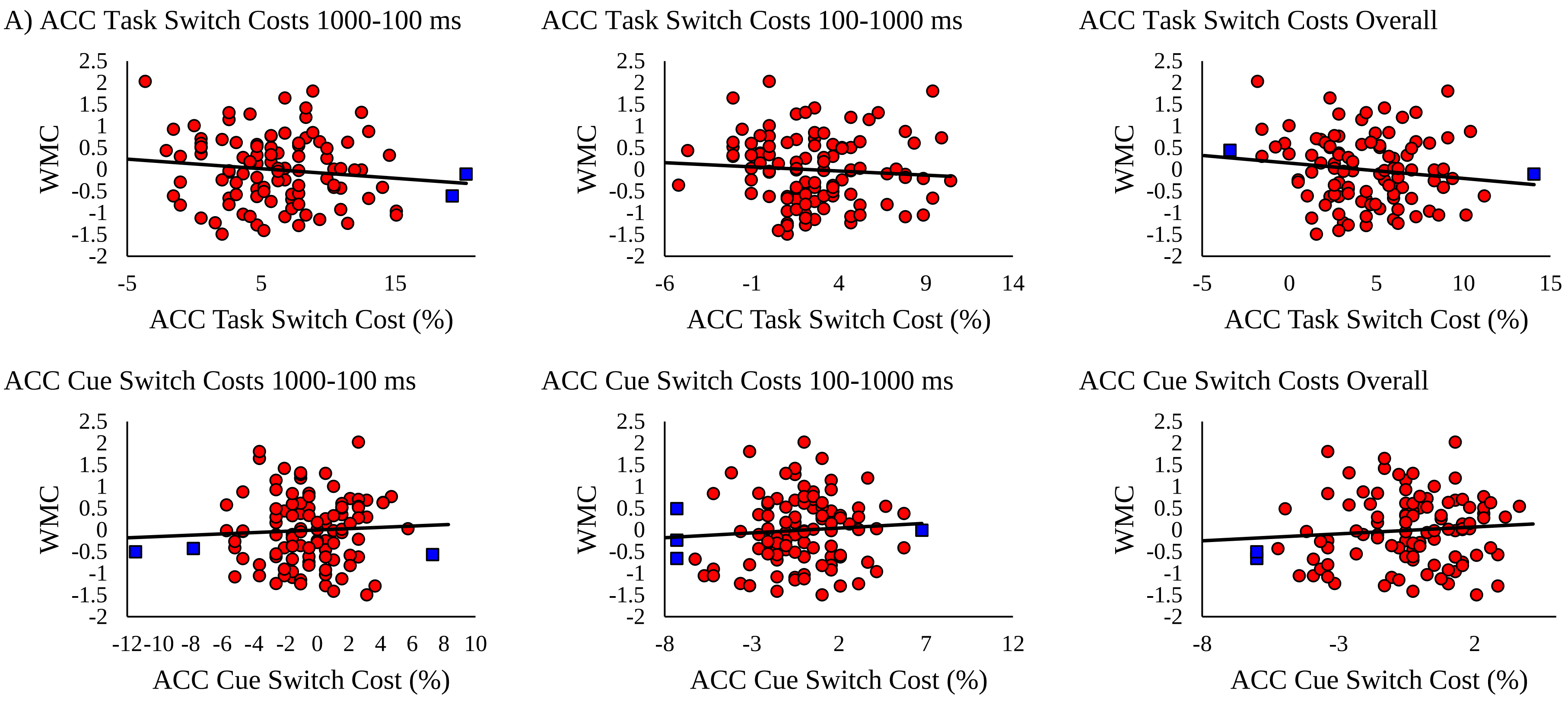
Descriptive M(SD) and Inferential Statistics for Congruent and Incongruent Trials, as well as Descriptive Statistics and Correlations with Working Memory Capacity (WMC) for Reaction Time (RT) and Accuracy (ACC) Congruency Costs with Outliers Included

	Congruent	Incongruent	Congruency Difference	Congruency Cost	WMC r
RT	608 (111)	648 (117)	$t(101) = -17.25$, $p < .001$	41 (24)	$r(100) = .01$, $p = .96$
ACC	97.3 (1.9)	91.2 (4.4)	$t(101) = 17.92$, $p < .001$	6.2 (3.5)	$\rho(100) = -.17$, $p = .09$

Table D-3b

Descriptive M(SD) and Inferential Statistics for Congruent and Incongruent Trials, as well as Descriptive Statistics and Correlations with Working Memory Capacity (WMC) for Reaction Time (RT) and Accuracy (ACC) Congruency Costs with Outliers Excluded

	Congruent	Incongruent	Congruency Difference	Congruency Cost	WMC r
RT	606 (110)	645 (115)	$t(99) = -18.23$, $p < .001$	39 (22)	$r(98) = .03$, $p = .79$
ACC	97.3 (1.9)	91.3 (4.3)	$t(100) = 18.41$, $p < .001$	6.1 (3.3)	$\rho(99) = -.17$, $p = .09$



A) ACC Task Switch Costs 1000-100 ms

ACC Task Switch Costs 100-1000 ms

ACC Task Switch Costs Overall

ACC Cue Switch Costs 1000-100 ms

ACC Cue Switch Costs 100-1000 ms

ACC Cue Switch Costs Overall

Figure D-1. Scatterplots demonstrating the relationship between A) working memory capacity (WMC) and accuracy (ACC) task switch costs and cue switch costs on the 2:1 cue to task mapping paradigm. These relationships are shown overall and across the two timing manipulations. Blue squares offer a visual depiction of mild outliers (1.5*IQR rule) which have remained in the present analysis.

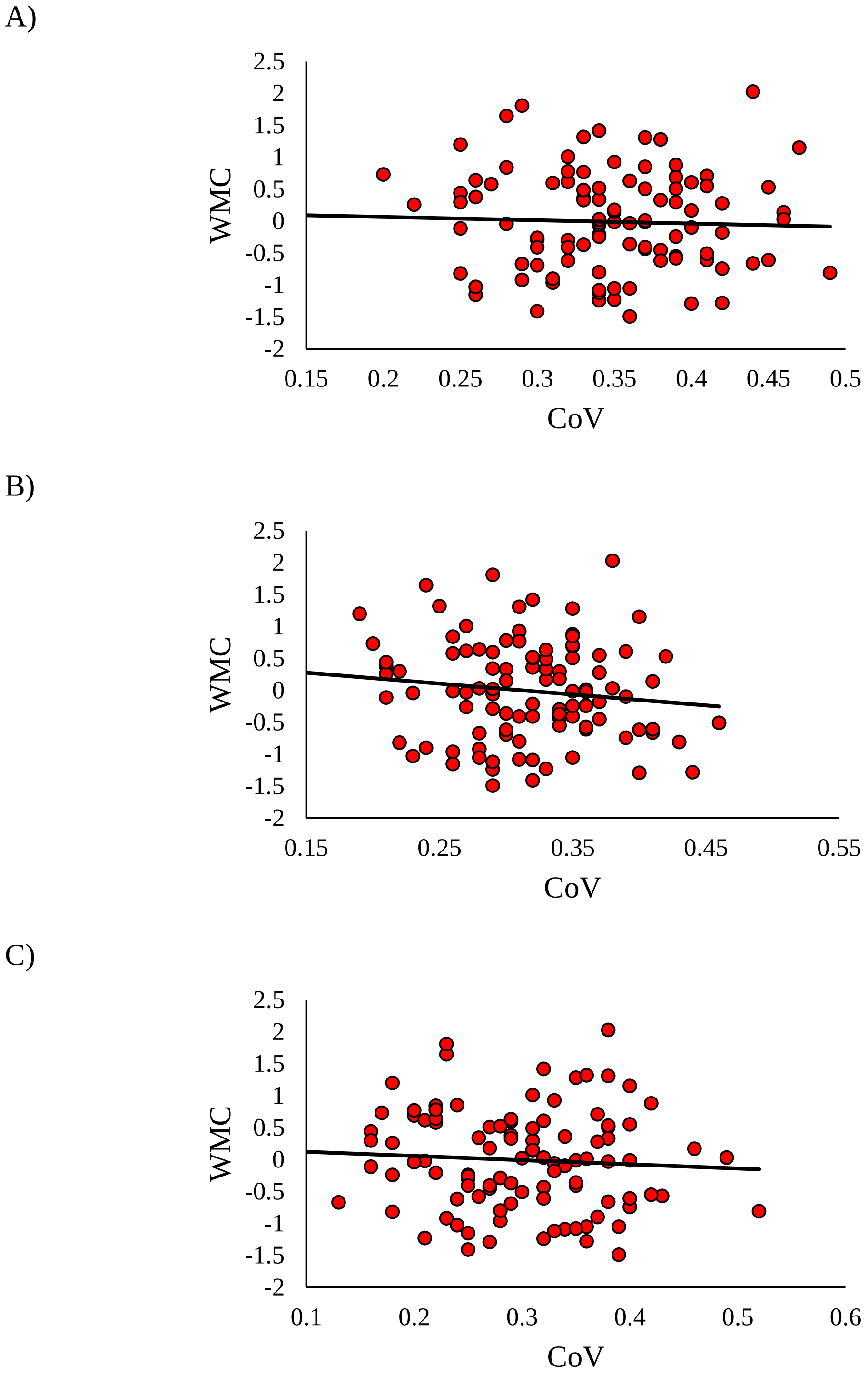


Figure D-2 Scatterplots demonstrating the relationship between A) working memory capacity (WMC) and coefficient of variation (CoV). This is shown A) overall, B) in the RCI:CSI 1000-100 ms condition, and C) in the RCI:CSI: 100-1000 ms condition. There were no outliers present in these analyses.