The relationship between working memory and sustained attention

By:

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Declaration

I, Hakan Atis, confirm that this thesis is my own work, and I declare that this thesis has not been submitted for an award at this, or any other university. The thesis was completed by the candidate under the supervision of Dr Claudia von Bastian and Dr Daniel J. Carroll.

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Thesis Abstract

Working memory (WM) is related to sustained attention. The resource depletion theory assumes that overloading working memory capacity (WMC) due to resource depletion results in poor sustained attention. However, the mindlessness theory suggests that when task is easy, lower intrinsic motivation leads to decreased sustained attention. Furthermore, the maintenance and disengagement theory suggests that attention control drive the relationship between WMC and fluid intelligence. However, previous research often conceptualises sustained attention as attention control. The first aim of this thesis is to test the resource depletion and mindlessness theory to understand under which conditions (set size, time-on-task and intrinsic motivation conceptualised as effort, perceived competence and interest) the relationship between individual differences in WMC and individual differences in sustained attention is strongest. We also aim to investigate whether sustained attention differs from attention control, and if so, whether sustained attention explains the relationship between WMC and fluid intelligence after accounting for attention control. In Chapter 2, we found that set size and effort moderated the relationship between WMC and sustained attention, that is, when the task was difficult (set size 6) and effort was low, there was no relationship between WMC and sustained attention. However, time-on-task, perceived competence, and interest did not have a moderating effect. In Chapter 3, we found that sustained attention was distinct but related to attention control. Neither sustained attention nor attention control mediated the relationship between WMC and fluid intelligence. This thesis tentatively supports the mindlessness theory and challenges the predominant theory that attentional processes are the main factor driving the association between WMC and fluid intelligence.

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CHAPTER 1 – Literature Review

Contributions:

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Claudia C. von Bastian (supervision, review and editing)

1. Introduction

Working memory (WM) and sustained attention play a vital role in successfully adapting to the challenges of many aspects of everyday life. For instance, some individuals may sometimes forget to attach a file while writing an email or experience lapses or fluctuations in attention while engaging in various activities such as reading a book or listening to a lecture. During these instances, temporary distractions, daydreaming, or occasional disengagement from the lecture, or difficulties in following and comprehending the storyline, recalling the sequence of events or the names of characters may occur. Such scenarios can range from daily life activities to academic and professional contexts, and might result in a number of negative outcomes, from academic failures to losing or forgetting task goals in daily life activities or challenges in sustaining attention during cognitive tasks. For example, professionals such as air traffic controllers, students, and truck drivers engage in tasks that involve extended period of activities such as consistently monitoring radars, multiple aircraft, changing situations, attending lectures, and memorizing routes. These tasks place simultaneous demands on sustained attention and WM.

Failures or lapses in either or both abilities in daily life, work or education may lead to accidents and problems. For example, failures in WM and sustained attention have been linked to some negative outcomes such as driving accidents (Edkins & Pollock, 1997; Galera et al., 2012; Louie & Mouloua, 2019; V. Ross et al., 2014; H. Zhang et al., 2023), potential problems with automation use in aircraft, power plants or driverless cars (Casner & Schooler, 2014; Gouraud et al., 2017; Szalma et al., 2004), challenges faced by lifeguards in maintaining focus on swimmers (Griffiths & Griffiths, 2013), document-related errors like forgetting to save an important document after working on it (Jones & Martin, 2003), some problems in education life (Alloway & Alloway, 2010; Gallen et al., 2023; Isbell et al., 2018; Unsworth et al., 2012; Wammes, Seli, et al., 2016, 2016). Moreover, impairments in WM and deficits in sustained attention are commonly observed in neurological conditions such as Attention Deficit Hyperactivity Disorder (ADHD, Huang-Pollock et al., 2012; Martinussen et al., 2005; Orban et al., 2014; Tucha et al., 2017) or learning difficulties (Alloway, 2009). Drawing from these examples, within the context of waking life and present-tense activities, both WM and sustained attention are important cognitive abilities crucial for functioning effectively, particularly considering that lapses in these abilities can potentially lead to serious consequences. Thus, their significance extends across various domains, including everyday tasks, academic success, professional responsibilities, and their relevance in neurological conditions. Now, I will introduce these two abilities separately, followed by their relationship to each other.

1.1 Working Memory (WM)

WM is a cognitive system that allows us to temporarily maintain and manipulate information according to the task goals (Engle, 2002, Mashburn et al., 2020). WM is like our mental workspace, allowing us to remember and work with information temporarily. It helps us hold onto things we need to remember while we're busy with other tasks. For example, imagine engaging in mental arithmetic where you need to multiply 17 by 8 without using pen and paper. You can employ the following strategy: Start by multiplying 7 by 8, which equals 56. Retain the number 6 in your mind, introduce the digit 5, proceed to multiply 1 by 8, add the result of 8 to the 5, and finally retrieve the 6 from your memory. This process will yield the answer, which is 136. The fact that WM enables concurrent information processing and storage in the present moment, as illustrated by these examples, is essential for activities in daily life (Baddeley et al., 2020; Baddeley & Hitch, 1974).

WM is associated with numerous cognitive processes and neurological conditions. WM is a limited-capacity system responsible for both maintaining and manipulating information. According to Cowan (2001), individuals can simultaneously hold about four chunks of information in their WM, where 'chunks' represent meaningful units or items grouped together to facilitate storage and retrieval. The capacity of WM varies among individuals. Some individuals have a higher capacity in WM, while some individuals have less. Therefore, these individual differences in their limited capacity of WM are predictive for a wide range of cognitive processes (Barrett et al., 2004). For example, the capacity limit of an individual's WM is strongly associated with fluid intelligence, referring learning new information and solving novel problems (Conway et al., 2003; Engle et al., 1999b; Oberauer et al., 2008; Unsworth & Engle, 2007b; Wilhelm et al., 2013), sustained attention (Unsworth et al., 2021; Unsworth & Robison, 2016), executive attention (Miyake & Friedman, 2012; Unsworth et al., 2021), and a set of other cognitive abilities (for a review, see Barrett et al., 2004). In addition to its association with cognitive abilities, impairments in WM are also linked to neurological conditions such as ADHD (Martinussen et al., 2005; for a review, see Orban et al., 2014) and cognitive declines across the lifespan (Park et al., 2002). The significance of working memory capacity (WMC) calls into question what WMC actually means and reflects as well as why individuals vary in their WMC and WMC is broadly predictive.

What is working memory capacity (WMC)?

WMC can be defined as a psychometric and an individual differences construct reflecting the capacity of an individual's working memory (Wilhelm et al., 2013). Individual differences in WMC reflect that individuals vary in the amount of information that can be held and manipulated in WM at any given time. Psychometrically, WMC is typically measured using complex span tasks. Complex span tasks have both a storage component and a manipulation component. A secondary processing task is interleaved within a memory span task. Participants are given various types of information to remember later, such as words, digits, or spatial orientations. Between each item presentation, they must make a decision, such as reading sentences or solving arithmetic problems, which may interfere with the memory task. Participants are required to remember items while performing a processing task after each item. Later, they recall the presented items in order. For example, in the numerical complex span task, participants are required to recall two-digit numbers and evaluate the accuracy of equations. During a complex span task, WMC refers to the number of items that can be recalled at one time (Conway et al., 2005; Daneman & Carpenter, 1980; von Bastian & Eschen, 2016).

Complex span tasks not only require the storage of information but also demand attentional processes, therefore, WMC measured by complex span tasks differs from short-term memory (STM), which only retains information for brief periods. The very early famous model of Atkinson and Shiffrin (1968), also called the multi-store memory model or the modal model, outlined a framework that human memory comprises three components. Briefly, sensory information comes to STM through attention and is retained and rehearsed there in a short time and then transferred to long-term memory. The multi-store model included a passive, limited-capacity buffer for short-term memory (Atkinson & Shiffrin, 1968). The story of measuring individual differences in WMC began, more than two decades ago, with the emergence of the differentiation between complex span tasks, used to measure WMC and simple memory span tasks, primarily designed for assessing STM. Simple memory spans, like digit span tasks, involve remembering a set of items and recalling them, without the order of recall varying. Memory span is measured by the list length at which memory errors start happening or by the total number of correctly recalled lists of varying lengths (assuming errors are more common with longer lists). However, these memory span tests had one limitation, they were less predictive of other abilities at least not as much as the WMC (for a review Mashburn et al., 2020).

Evidence supporting the clear distinction between STM and WMC comes from a study that examines the relationships between these two latent variable constructs using structural equation models (Engle, 1999). This study employed latent variables to investigate whether STM and WMC were distinct or not. They found that STM and WMC were distinct yet related to each other. Furthermore, WMC was found to be associated with fluid intelligence, which refers to learning new information and solving novel problem, whereas STM was not. These findings suggest that WMC and fluid intelligence are related to each other above and beyond STM because WMC and fluid intelligence require controlled attention in the face of distraction while actively holding information, but STM does not include controlled attention. Furthermore, the first complex span task, the reading span task, proved effective in predicting reading comprehension (Daneman & Carpenter, 1980), but simple span task was not correlated to reading comprehension. The difference between complex span tasks and simple span tasks arises from the inclusion of a secondary task in the complex span tasks, which interferes with the memory task. Therefore, these suggest that WMC is more complex construct compared to STM. In addition, compared to simple span tasks, complex span tasks have been highly predictive for other cognitive abilities because they require also attentional processes as well as storage (Engle et al., 1999b).

Subsequent working memory models expanded on the concept of the short-term store by emphasizing attentional component of WM for both information storage and processing (Baddeley & Hitch, 1974; Cowan, 1988; Engle, 2002). In the literature, the attentional component of WM has been referred as the central executive (Baddeley & Hitch, 1974), controlled attention (Cowan, 1988), attention control (Engle, 2002), supervisory attentional system (Norman & Shallice, 1986). The term ‘attention control’ will be used in this thesis to refer to these concepts mentioned above.

Attention control refers to the ability to maintain an operative goal, which influence current information and action, and goal relevant information in the presence of distraction (von Bastian et al., 2020). To understand better what attention control is, it is crucial to differentiate between two forms of information processing: controlled processing and automatic processing. This theoretical framework is also known as the dual processing model (Norman & Shallice, 1986). While some actions do not require conscious and effortful processing, known as automatic processing, others need conscious awareness, effort, or controlled processing. Interactions between automatic and controlled processing determine behaviour. When objects in our environment capture our attention without us trying, it is called bottom-up (Egeth & Yantis, 1997). For example, imagine walking down the street and suddenly noticing a bright flash of light out of the corner of your eye, drawing your attention to it involuntarily. Another example of bottom-up processing could be when you're in a crowded room and hear your name mentioned in a conversation in the room. Even though you weren't actively listening for it, the sudden occurrence of your name captures your attention. These automatic processes happen without us even realizing it and are considered the default mode of information processing (Conway et al., 2001).

Controlled attention (Egeth & Yantis, 1997) plays a significant role in determining how much automatic processing affects our thoughts, feelings, and actions. When attention is drawn to a stimulus that conflicts with our goals, or when we have conflicting goals, we need to bring our attention under control to resolve the conflict. For instances, students are trying to focus on studying, but their phones receive notifications. The impulse to check their phone conflicts with their goal of studying. To resolve this conflict, students need to exert control over their attention by ignoring the distractions and refocusing on their study material. In such situations, individuals actively maintain or increase the activation of relevant goals, deliberately activate necessary goals if they're not already activated, and suppress irrelevant goals. This deliberate manipulation of our mental representations through attention control is known as controlled processing (for a review, see Barrett et al., 2004; Mashburn et al., 2020). Within the context of dual processing, one prominent model of WM, the attention control theory of WMC, suggests that individuals vary in their WMC due to differences in attention control; some control their attention, while others have weaker abilities in this regard (Engle, 2002, 2018; Engle & Kane, 2004).

The Attention Control Theory of WMC

The attention control theory is one of the most influential theoretical accounts explaining individual differences in WMC and why WMC is more predictive of complex cognition. This theory states that individual differences in WMC reflect individual differences in attention control (Engle, 2002; Engle & Kane, 2004; Kane et al., 2007). According to this theory, "*WMC is not really about storage or memory per se, but about the capacity for controlled, sustained attention in the face of interference or distraction"* (Engle et al., 1999a, p. 104). In other words, WMC is responsible for actively maintaining relevant information while inhibiting irrelevant information, even in the presence of potential distractions. Indeed, many findings indicates that complex span tasks are frequently related to tasks specifically designed to measure attention control (for a review, Unsworth et al., 2021). Although the complex span tasks themselves might not directly assess attention control, the variance in performance on these tasks is associated with attention control abilities. In other words, individuals who perform better on complex span tasks tend to also have better attentional control, even though the tasks were not explicitly designed to measure attentional control. In addition, regarding the tasks that assess these two abilities, the attentional control task requires minimal memory demand compared to complex span tasks. Therefore, the unique variance observed in complex span tasks indirectly is assumed to reflect attention control abilities.

Some direct evidence to support the attention control theory of WMC come from quasi-experimental designs. In these kinds of studies (Heitz & Engle, 2007; Kane et al., 2001; Kane & Engle, 2003; Unsworth et al., 2004), researchers typically assess a considerable number of participants using a measure of WMC and then divide them into groups based on their scores, often using tertiles or quartiles. The groups with the highest and lowest scores were labelled as the high-span group and low-span group, respectively, and their performance on tasks measuring attention control was compared. If attention control was indeed predictive of WMC, differences in performance between high- and low-span groups should be evident whenever a task necessitates controlled processing. Hence, quasi-experimental studies provide support for the attention control theory of WMC.

Kane, Bleckley, Conway, and Engle (2001) found high-span and low-span WMC differences in anti-saccade task performance. They used an anti-saccade task to measure attention control, which involves inhibiting the reflexive tendency to look at a stimulus, and a prosaccade task to measure reflexive orienting, which involves looking directly at a stimulus. In the anti-saccade task, participants are instructed to look away from a suddenly presented visual stimulus, typically by making a saccadic eye movement in the direction opposite to the stimulus. It requires participants to inhibit the automatic response of looking toward the stimulus and instead perform a voluntary eye movement in the opposite direction. The task measures the ability to suppress prepotent responses and maintain goal-directed behaviour despite interference (Everling & Fischer, 1998). The prosaccade task assesses the ability to orient attention reflexively towards a target. Participants are required to quickly and accurately direct their gaze towards the target stimulus. Kane and colleagues (2001) hypothesised that there would be variations in performance between different spans on anti-saccade trials, as success on these trials involves consciously avoiding looking at the peripheral cue and instead making a saccade in the opposite direction according to the task goal. However, they did not expect differences in performance on prosaccade trials because looking towards motion is an involuntary, automatic response. In the prosaccade task, both span groups performed similarly in identifying targets, indicating similar automatic orienting abilities. However, in the anti-saccade task, low-span participants exhibited slower and less accurate performance compared to high-span participants, highlighting differences in attentional control. This result suggested that low-spans were less capable of controlling their attention than high-spans. This evidence support the attention control theory regarding in the anti-saccade task.

Similarly, Unsworth, Schrock, and Engle (2004) conducted an experiment to replicate and expand on previous findings regarding span differences in anti-saccade performance. In their studies, participants were required to initiate saccades in the appropriate direction, and eye movements were tracked using an eye tracker. They consistently observed span differences on anti-saccade trials, with high-span individuals being less likely to initiate saccades towards peripheral cues. In addition, low-span participants, who may tend to persist with current goals, showed slower initiation of correct prosaccades when prosaccade and anti-saccade trials were mixed within a block. This finding suggests that high-spans was better not only in inhibition but also in orienting the focus of attention than low-spans. These results support the idea that individual differences in attention control contribute to variations in WMC.

Another study investigated differences between individuals with low and high working memory spans in their ability to inhibit environmental distractions. Heitz and Engle (2007) examined how low-span and high-span individuals differ in their ability to focus their attention on a central target while dealing with distractors in a letter flanker task (Eriksen & Eriksen, 1974). In this flanker task, participants were presented with sequences of letters and tasked with identifying the central letter. These sequences can either consist entirely of the same letters (congruent, e.g., *SSSSS*) or include one letter that is different from the others (incongruent, e.g., *SSHSS*). The flanker interference effect was determined by calculating the difference between the average reaction time on incongruent trials and the average reaction time on congruent trials. They found that individuals with high-spans were quicker to direct their focus to the target, thus reducing the impact of peripheral distractors sooner than those with low-spans. These quasi-experimental studies provide important information about the predictive nature of WMC and open the door to the idea that the ability to control one's attention mediates the relationship between WM and complex cognition like fluid intelligence.

Studies investigating why WM predict complex cognition have focused on fluid intelligence because WM is highly correlated with fluid intelligence (Conway et al., 2003; Engle et al., 1999a; Oberauer et al., 2008; Unsworth et al., 2014; Unsworth & Engle, 2007b; Wilhelm et al., 2013). Fluid intelligence (Gf) is the ability to solve new or abstract problems (Cattell, 1963; Horn, 1968). Gf is associated with various crucial skills such as learning, abstract thinking, problem-solving, comprehension and academic achievement (Cattell, 1971; Deary et al., 2007; see, Unsworth et al., 2014). In the literature, Gf is frequently measured by the Raven advanced progressive matrices, Number Series, Letter Series, Paper Folding tasks. For example, The Raven Advanced Progressive Matrices is a standardized test designed to assess abstract reasoning skills and the ability to infer rules and relationships in visual patterns. It comprises 36 items arranged in increasing levels of difficulty. Each item presents a 3 × 3 matrix of geometric patterns, with one pattern missing. Participants are tasked with selecting the correct pattern from eight alternatives to complete the overall sequence. WMC is a strong predictor of Gf and it has even been debated whether they are psychometrically isomorphic constructs (e.g., Chuderski, 2013; Kyllonen & Christal, 1990). The relationship between them and which mechanisms can explain this relationship is still a matter of debate.

One prominent theory explaining this relationship between WM and Gf is the maintenance and disengagement theory, which is an extension of WMC as attention control theory (Engle, 2018; Shipstead et al., 2016). The maintenance and disengagement theory posits that WM is closely related to Gf through the mechanisms of attention control. According to this theory, individuals with higher WMC have greater ability to both maintain focus on relevant information, and to disengage from irrelevant information. This attention control allows them to effectively allocate attentional resources to solve complex problems, leading to better performance on tasks measuring fluid intelligence. In other words, individuals with higher WMC are better able to filter out distractions and maintain attention on task-relevant information, which in turn facilitates problem-solving and abstract reasoning abilities associated with fluid intelligence.

However, WM and Gf are reliant on attention control mechanisms to different degrees: maintenance and disengagement. While WM primarily involves maintaining information, Gf primarily involves disengaging from irrelevant information. However, both processes incorporate these mechanisms to varying extents. Maintenance helps focusing attention to prevent relevant information from being lost due to interference (Cowan, 2001; Oberauer et al., 2008), while disengagement from irrelevant information decreases the likelihood of fixating on outdated or currently irrelevant information (Storm, 2011). According to the theory, performance on tasks measuring fluid intelligence is largely influenced by an individual's ability to disengage from outdated information because Gf tests prioritize inhibition. This emphasis on inhibition allows individuals to inhibit outdated information. In fluid intelligence tasks (described earlier), the test taker must demonstrate the ability to consider multiple options, evaluate their suitability, and choose the most appropriate one, which reflects cognitive flexible or inhibition irrelevant information underlying fluid intelligence tasks. In complex span tasks, the primary attentional mechanism is maintenance, as the objective is to remember items in memory. Maintenance and disengagement are responsible for both types of tasks, but they serve to different degrees (for a review, Shipstead et al., 2016).

Shipstead and Engle (2013) provided some evidence regarding the maintenance and disengagement. They found that in a WM task, extended inter-trial intervals between items to be recalled resulted in higher estimates of storage capacity. This suggests that individuals disengage from the previous item to be remembered, thereby reducing proactive interference, which refers to the initial memorized information interfering with the encoding or retrieval of new information. Moreover, they found that inter-trial intervals did not change the relationship between storage capacity scores in the visual arrays task and WMC but increased the correlation between Gf and storage capacity scores. This suggested that high-Gf individuals were capable of utilizing the additional time during long inter-trial intervals to disengage from the memory items from the previous trial. These findings pose a challenge to interpreting the WMC–Gf relationship solely from a maintenance perspective.

Shipstead et al. (2014) investigated whether WM is related to Gf through the broader mechanisms of attention control because in this theory, maintenance and disengagement information was conceptualised as two components of a top-down attentional process. In a complex span task, individuals first encode and memorize items in primary memory, followed by engaging in a secondary attention control task. Subsequently, they continue to memorize additional items in primary memory in subsequent trials. At the end of the task, individuals retrieve those items from secondary memory. Hence, they examined five latent variables factors, including primary memory (short-term memory, limited capacity storage), secondary memory (retrieval from long-term-memory), attention control, WMC and Gf. Attention control was assessed in three ways: by measuring anti-saccade accuracy, and by assessing interference effects in the colour Stroop and arrow flanker paradigms. The latent factor of primary memory was defined by accuracy in list recall within limit of primary memory while the secondary memory was loaded by the list recall accuracy once the limit of primary memory was exceeded (i.e., when the number of recalled items exceed 7; Tulving &

Colotla, 1970). In other words, words recalled with seven or fewer intervening items between presentation and recall were categorized as primary memory, while those recalled with more than seven intervening items were classified as secondary memory. They found that after accounting for the effects of primary memory, secondary memory, and attention control, the association between WMC and GF was not significant. This suggests that the association between WMC and Gf is fully mediated by their relationships with attention control, primary memory, and secondary memory.

Although both quasi-experimental studies and the study involving structural equation modelling have provided strong evidence that WMC differences are related to individual differences in attentional control, these studies have primarily focussed on the inhibition of external distractions. For example, tasks like the flanker task, as described earlier, assess the ability to resist distractions from the perceived environment or irrelevant external information. In these types of tasks (i.e., Flanker Stroop, Anti-saccade) attention must be actively redirected away from distracting stimuli. In addition, tasks such as Stroop task, anti-saccade task, and Go/no-go task assess the ability suppress habitual, prepotent, or automatic responses (Friedman & Miyake, 2004; von Bastian et al., 2020). However, sustained attention, which is assumed to be another aspect of attentional control (Engle et al., 1999a; Tsukahara & Engle, 2023; Unsworth & Robison, 2020) has been ignored in the studies described above. In recent years, there has been a growing interest in investigating the relationship between individual differences in WMC and individual differences in sustained attention.

1.2 Sustained Attention

Sustained attention refers to the ability to continuously engage on a task and to maintain focused attention during the task, for a prolonged period of time. This ability is also called vigilance (Langner & Eickhoff, 2013; Robertson & O'Connell, 2010; Unsworth & Robison. 2020). It is essential for most everyday tasks to be able to maintain attention.

However, sustaining attention over time can be challenging, and lapses in attention can sometimes have very serious consequences. Failures in sustaining attention are associated with poorer performance on higher-level tasks such as reading comprehension (Stern & Shalev, 2013), academic performance (Calkins et al., 2018; Wammes, Boucher, et al., 2016), WMC and attentional control (Unsworth et al., 2010). Despite its importance, there is less research on sustained attention as opposed to other aspects of attention, such as shifting and inhibition. Therefore, it is important to better understand the mechanisms underlying of individual differences in sustained attention.

A common finding in the literature is that on tasks that require sustained attention, task performance tends to significantly decrease over time (Hopstaken et al., 2015; Mackworth, 1948; Parasuraman, 1979). As time progresses during the task, there is a decline in behavioural performance (reflected by both longer RTs and lower accuracy), and in self-reported alertness, and self-reported task engagement, accompanied by an increase in mind wandering (Mackworth, 1948; Unsworth et al., 2021; Unsworth & Robison, 2016). The decline in performance observed in sustained tasks is commonly known as vigilance decrement. Historically, following World War II, Mackworth (1948) investigated the deteriorating vigilance of British naval radar operators, who increasingly missed crucial radar signals during their watch periods. Mackworth (1948) developed the Mackworth Clock Test (MCT) to simulate the sustained attention required in radar monitoring tasks. Participants were asked to monitor a clock, detecting occasional "skips" in the clock hand's movement. Mackworth observed that sustained attention decreased over time, reflecting the challenges faced by radar operators in maintaining attention during long watch periods.

Sustained attention is an unitary construct that contains a number of different aspects: attention fluctuations, lapses of attention, and mind wandering (Esterman & Rothlein, 2019; Mackworth, 1948; Unsworth, Robison, et al., 2021a). Research on sustained attention is characterized by its emphasis on observing how individuals perform on a single task over a period of time. The aim is to understand both the variations in performance within individuals and the differences in overall ability to maintain consistent task performance. These aspects of sustained attention can be measured using both behavioural and subjective assessments.

Attention fluctuations refers to broader shifts in attentional focus over time, which can include both periods of heightened and diminished attention (Esterman & Rothlein, 2019; Unsworth & Miller, 2021). During a task, attention is not consistently stable but rather fluctuates. There are periods where attention is focused and robust, leading to effective task engagement and performance. However, there are also moments where attention diminishes, resulting in lessened task involvement and suboptimal performance.

In the literature, attention fluctuations are assessed based on the variability in reaction times (RTs), indexed by the standard deviation of RTs across trials, in sustained attention tasks (Esterman et al., 2013). For example, in sustained attention tasks such as simple RT tasks and the Psychomotor Vigilance Task (PVT; Dinges & Powell, 1985; Lim & Dinges, 2008), participants are required to respond quickly to a visual stimulus, typically a light or a symbol, by pressing a button as soon as they see it. RT variability refers to the degree of inconsistency in RTs across multiple trials of the task. It can be quantified using standard deviation, which measures the spread of RTs around the mean. A higher standard deviation indicates greater variability in RTs, suggesting more attention fluctuations.

Lapses of attention refer to moments when individuals experience slower responses compared to their typical RTs. In brief periods during a task, focused attention may diminish or wander away from the current task. Lapses of attention are associated with both attention control and the level of alertness, which refers to a state of active attention and readiness to respond (Unsworth, Robison, et al., 2021a; Unsworth & Robison, 2020). Lapses of attention are typically assessed through two common methods. One of them is to examine longer RTs in response to each stimulus. This approach reflects the varying degrees of sustained attention individuals exhibit during the task, indicating how vigilant they are in maintaining focus and responsiveness. The second method requires to detect infrequent target. This approach enables researchers to assess sustained attention and the ability to maintain focus amid distractions.

Lapses of attention are typically measured by simple RT tasks and the PVT, where participants are required to respond quickly to stimuli. In these tasks, longer RTs are used as the dependent variable to measure lapses of attention. Longer RTs indicate delays in responding to stimuli, which can occur when individuals experience lapses in attention because attention is momentarily diverted. In the context of sustained attention tasks like the PVT or simple RT task, measuring RTs involves focusing on the slowest responses, which represent the longest durations. One common method is to calculate the cutoff point for longer RTs based on a percentile of the RT distribution, such as the slowest 20% (Langner & Eickhoff, 2013; Lim & Dinges, 2008; Robison & Brewer, 2019; Unsworth et al., 2021; Unsworth & Robison, 2017b, 2020). The other method is the tau (τ) parameter from ex-Gaussian distribution. τ refers to longer responses in a series of RT measurements (all trials during a simple RT or PVT task) and can serve as an index of attentional lapses. In other words, τ represents the mean of the right tail of the RT distribution. The right tail of the distribution includes longer RTs, which are associated with lapses of attention or slower processing speed (Unsworth et al., 2010). By focusing on the right tail of the distribution, τ captures the average duration of these longer RTs, providing insight into the frequency and duration of attentional lapses during the task. Therefore, a higher τ indicates a longer average duration of attentional lapses, while a lower τ suggests shorter lapses and better sustained attention (Unsworth et al., 2010).

Lapses of attention are also studied with the continuous performance paradigms. The tasks used in this paradigm are commonly detection tasks, go/no-go, continuous performance tasks (CPT), and the Sustained Attention to Response Task (SART). In these tasks, participants monitor displays for prolonged periods and respond when low-probability critical signals appear. In other words, participants are required to maintain focus and respond quickly and accurately to rare target stimuli (11%) while minimizing errors of omission (missing targets) and commission (responding to non-targets; non-target is 89%). Conversely, some researchers employ a task design where participants are presented with 89% go trials (responding to non-targets) and 11% no-go trials (withholding to targets). Lapses of attention are characterized by reflexive responding or temporary disruptions in sustained attention, resulting in missed (accuracy) or delayed responses (RTs) to rare target stimuli (Cheyne et al., 2009; McVay & Kane, 2009; Robison & Brewer, 2022).

Mind-wandering can be defined as a shift in attention away from a primary task towards self-generated thoughts or internal thoughts (McVay & Kane, 2009, 2012; Mrazek et al., 2012; Smallwood & Schooler, 2006). Mind wandering is often measured using self-report techniques, also called thought probes, where participants are periodically asked to report whether their thoughts were related to the ongoing task or if they were unrelated (task-unrelated thoughts, TUTs) during a task. While thought probes techniques provide information about participants' subjective experiences of mind wandering, they do not provide behavioural measurements such as RTs or accuracy. This lack of behavioural measurements can make it challenging to objectively examine mind wandering. Taken together, sustained attention encompasses lapses of attention, attention fluctuations, and mind wandering, all of which can be measured using both behavioural and subjective assessments. In these measurements, sustained attention performance decreases with time-on-task (Unsworth & Robison, 2020).

In terms of explaining the decline in sustained attention performance over time, and why individuals struggle to maintain focus on a task, there are two main theories: the resource depletion theory (Caggiano & Parasuraman, 2004) and the mindlessness theory (Manly, 1999; Robertson et al., 1997). The resource depletion theory suggests that the decline in sustained attention performance over time is attributed to the gradual depletion of limited attentional resources essential for maintaining focus. Studies based on self-reports have consistently highlighted the demanding nature of sustained attention tasks (for a review, see Warm et al., 2008). As individuals continuously exert effort to sustain their attention, these limited resources are gradually drained, contributing to a decline in performance. Consequently, the available pool of limited resources diminishes at a faster rate than it can be replenished, resulting in an increase of attention lapses over time, and ultimately leading to a decline in overall performance (Hancock, 2017; Head & Helton, 2014; Helton et al., 2005; Helton & Warm, 2008).

The second theory accounting for the decreases in sustained attention is the mindlessness theory (Manly, 1999; Robertson et al., 1997). The mindlessness theory suggests that lapses in sustained attention tasks occur over time because individuals disengage from the task due to monotony, under-stimulation or boredom (Scerbo, 1998). In contrast to the resource depletion theory, the mindlessness theory proposes that sustained attention tasks are boring and monotonous. For example, Manly and colleagues (1999) utilized two variations of the Sustained Attention to Response Task (SART) to investigate the effects of task monotony. In the infrequent target version, participants were instructed to withhold from responding to infrequent target stimuli (appearing on 11% of trials), while in the frequent target version, they were required to withhold responses to stimuli that comprised 50% of the targets. In the infrequent target version where participants had to respond to 89 percent of the stimuli and withhold 11 percent of the stimuli, by increasing the monotony of the task, they found that performance was poorer in the rare target condition. Consequently, this study suggests that in monotonous tasks where responses become more automatic and target stimuli are exceedingly rare, attention may drift away from the primary task, leading to declines in sustained attention performance. This study further proposes that intrinsic motivation may also contribute to performance decrements in sustained attention, as individuals may become distracted by task monotony and boredom.

The mindlessness theory can be conceptualized as intrinsic motivation. Intrinsic motivation refers to engaging in activities for the inherent enjoyment or satisfaction they provide, rather than for external rewards or incentives (Ryan & Deci, 2017, 2020). Intrinsic motivation involves willingly putting effort into activities because they are personally enjoyable, satisfying, and align with one's perceived competence and interests. For example, in a football match, the goalkeeper, despite infrequent ball contact, maintains attention by closely tracking the ball's movements. When facing a critical shot, the goalkeeper's sense of competence surges as they successfully block the attempt, heightening their focus on the ball. Conversely, during less eventful game periods, their sustained attention may diminish, potentially increasing the risk of conceding a goal. Indeed, some studies have reported a positive association between effort, task interest, and sustained attention performance (Unsworth et al., 2022; Unsworth & Robison, 2020). However, there is no evidence regarding the relationship between perceived competence and sustained attention. Collectively, these theories (resource depletion and mindlessness) provide different perspectives on why sustained attention performance tends to decline over time and offer insights into the underlying mechanisms involved in maintaining focus during prolonged tasks.

In addition, some evidence comes from structural equality modelling study why individuals experience lapses of attention throughout the task. In a recent study conducted by Unsworth, Robison and Miller (2021), individual differences in sustained attention were investigated. The aim was to understand how various predictors contribute to unique variance in this construct. Unique variance refers to the portion of variability in a particular variable that is not accounted for by other variables in the model. Participants engaged in a series of attention control tasks (Stroop, anti-saccade, cued visual search), working memory tasks (complex span tasks), and sustained attention tasks indexed by RTs (PVT, SART, choice RT, continuous tracking, whole report visual working memory). They also completed assessments of task-unrelated thoughts, task-specific (intrinsic) motivation, alertness, and trait factors. Behavioural indicators of sustained attention were found to correlate and load onto a single general factor. This factor was distinct from, yet correlated with, factors related to attention control and task-unrelated thoughts. Moreover, the sustained attention factor was linked to working memory capacity, processing speed, intrinsic motivation, alertness, boredom proneness, and self-reported cognitive failures in everyday life. Structural equation modelling revealed that attention control, task-unrelated thoughts, shared variance across task-unrelated thoughts, intrinsic motivation, alertness, and boredom proneness each accounted for unique variance in sustained attention. These findings emphasize the widespread nature of sustained attention across various tasks and situations and highlight the multifaceted factors contributing to individual differences in sustained attention.

In addition, it seems that the study of Unsworth and colleagues (2021) is consistent with both the resource depletion theory and the mindlessness theory. The correlation between sustained attention and attentional control aligns with the idea that the attentional resources required for sustaining attention are closely linked to those involved in attentional control. This is because the finding seems to suggest that depletion or failures of attentional control may lead to lapses in sustained attention over time. In addition, the finding that sustained attention is related to alertness, task motivation and boredom, appears consistent with the mindlessness theory, especially when considered alongside intrinsic motivation. That is because it suggests that sustained attention may fluctuate, or lapses based on factors such as intrinsic motivation and alertness levels. According to the mindlessness theory, individuals may experience lapses in attention when they become disengaged from a task due to factors like boredom or lack of motivation. Therefore, the observed associations between sustained attention and these variables provide support for the idea that sustained attention may be influenced by internal states and motivations. Taken together, the resource depletion and mindlessness theories appear to offer complementary information about individual differences in sustained attention.

In addition, it is important to understand whether sustained attention and attention control are different constructs. Previous research suggests that sustained attention comprises two key aspects of attentional processes: attentional control and alertness referring state of readiness for processing and responding (Luna et al., 2022; Oken et al., 2006). Unsworth, Robison and Miller (2021) found that attention control and sustain attention are distinct. The study revealed a strong correlation between sustained attention and the attention control factor (r = .70), consistent with previous studies (Kane et al., 2016; Unsworth, 2015; Unsworth & Spillers, 2010). Furthermore, Luna et al. (2022) found that failures in attention control were more strongly related to poor sustained attention rather than failures in alertness. They examined the association between attention control and sustained attention using their developed task, the ANT for Interactions and Vigilance—attention control and alertness components (ANTI-Vea). This task evaluates attention control and alertness components of sustained attention. This task includes three subtasks. The first subtask, designated ANTI, includes a flanker task that inhibits prominent task-relevant distractions. The second subtask features a signal-detection task akin to the SART, focusing specifically on the attention control component of sustained attention. The third subtask is modified from a simple reaction time or PVT task, evaluating alertness component of sustained attention as the ability to maintain alertness levels of attention to promptly react to stimuli from the environment. They found that the decline in the attention control aspect of sustained attention, but not in the alertness aspect, was moderated by changes in attention control throughout the duration of the task. In other words, the decline in the attention control component of sustained attention, as measured by task like the SART, was more pronounced in participants who experienced a decrease in attention control over time-on-task compared to those whose attention control performance did not decrease. However, RT variability and lapses in sustained attention (alertness aspect) was not moderated by attention control. This study suggests that sustained attention comprises two components: attentional control and the more basic process of arousal or vigilance and the decrement in sustained attention is primarily attributed to a decrease in attention control.

Sustained attention is also related to alertness or automatic stimulus selection, enabling an individual to be prepared for incoming stimuli. For instance, when anticipating an important email, the sustained attention or alertness network maintains a state of readiness to notice its arrival. Fan and colleagues (2002) developed the Attention Network Test (ANT) to explore whether there is a correlation between individual variances in sustained attention assessed through PVT, involving the ability to respond quickly to stimuli, and attention control network evaluated through the flanker task. They found no significant correlation between individual variations in task performance related to these networks, indicating that sustained attention and attention control are separate aspects of attentional processes.

Collectively, what exactly sustained attention reflects seems to depend on how we measure it. It seems when sustained attention is measured by the task such as SART, CPT, go/no-go and a signal detection, individual differences in sustained attention reflect attention control. If sustained attention is assessed through vigilance paradigms such as the RT task or the PVT, sustained attention reflects alertness level and promptly react to stimuli from the environment. Therefore, it is unclear whether sustained attention is a different construct from attention control, especially when sustained attention is assessed using tasks without any distractions.

Table 1.1 provides an overview of the key constructs introduced in the thesis. Next, we introduce the relationship between WM and sustained attention.

Table 1. 1

Summary of the key constructs and measures

Construct	Definition	Measures
Working Memory Capacity (WMC)	Working memory is the ability to maintain and process information in the present moment. The capacity of working memory is limited to about four chunks of information at a time (Cowan, 2001).	***Complex span*** tasks require simultaneous information storage and processing (Conway et al., 2005; Unsworth & Engle, 2007a; von Bastian & Eschen, 2016). Previous studies have often administered only this task, thereby potentially overly emphasising this specific task type when exploring the underlying factors of WMC. To address this, in Chapter 3, we administered binding, updating, and continuous reproduction, which measure different aspects of WMC. Furthermore, these tasks, along with complex-span tasks, contribute to the general WMC factor (Wilhelm et al., 2013). ***Binding*** tasks assess binding of items to their contexts (Oberauer, 2005). ***Updating*** tasks require encoding, maintenance and substitution of no longer relevant information with novel information (Miyake et al., 2000; von Bastian et al., 2016). ***Continuous reproduction*** tasks require reproducing stimuli features on a continuous scale, thereby allowing for assessing the precision of representations and their recall (Zhang & Luck, 2008).
Sustained Attention	The ability to sustain consistent attention on a task over extended periods of time.	***Simple RT*** tasks require participants to respond to stimuli consistently over time (for a meta-analysis, see Langner & Eickhoff, 2013). Performance in these tasks typically declines with increasing time-on-task (Mackworth, 1948; Unsworth et al., 2021; Unsworth & Robison, 2020). Longer RTs, specifically the τ parameter from the Ex-Gaussian distribution, are used as indicators of attentional lapses (Unsworth et al., 2020), while RT variability (SD_{RT}) serves as an indicator of attention fluctuation (McVay & Kane, 2009).
Attention Control	The ability to maintain a goal and goal-relevant information in the face of distractions (von Bastian et al., 2020).	Attention control tasks require the inhibition of prepotent response in conflict situations or the suppression of distraction caused by habits (Friedman & Miyake, 2004; von Bastian et al., 2020). ***Stroop*** tasks require suppressing the dominant response to the value of the digit and instead focusing on the task-relevant aspect of identifying the number of digits presented (Salthouse & Meinz, 1995). ***Simon*** task measures attention control by requiring participants to inhibit the tendency to respond based on the spatial location of the stimulus (either left or right) and instead focus on identifying the colour of the circle, particularly in incongruent trials where the stimulus location conflicts with the designated response button location (Simon, 1969). ***Go/No-Go*** task assesses

		inhibitory control by requiring participants to suppress the automatic response to frequently presented stimuli while successfully withholding responses to infrequent stimuli (Eimer, 1993). Previous studies have showed that these tasks load onto the attention control factor (Burgoyne et al., 2023; Chuderski & Jastrzębski, 2018).
Fluid Intelligence (Gf)	The ability to reason and solve novel problems, independent of previously acquired knowledge (Cattell, 1963).	Fluid intelligence tasks are designed to assess an individual's ability to solve novel problems, reason abstractly, and think logically, independent of prior knowledge. ***Raven*** consists of a series of visual puzzles requiring participants to identify the missing piece from a set of options that complete a pattern (Arthur et al., 1999; Arthur & Day, 1994). ***Letter sets*** task presents participants with sets of letters and requires them to determine which set does not belong based on logical rules (Ekstrom et al., 1976). ***Paper folding*** task presents participants with a sequence of diagrams illustrating how a piece of paper is folded and subsequently punched. Participants are required to predict the resulting hole patterns when the paper is unfolded (Ekstrom et al., 1976). This task assesses spatial reasoning and the ability to visualize transformations in three-dimensional space. Previous studies have shown that these tasks load onto the fluid intelligence factor as they assess abstract reasoning and the ability to identify patterns and relationships (Nusbaum & Silvia, 2011; Redick et al., 2016).
Intrinsic Motivation	Intrinsic motivation refers to engaging in activities for their inherent satisfaction, rather than external rewards or pressures. When individuals perceive a task as interesting, feel competent in their ability to complete it, and invest effort, their intrinsic motivation is heightened (Ryan & Deci, 2017, 2020).	Previous studies reported that sustained attention performance was correlated with lower self-reports task engagement and intrinsic motivation (Manly, 1999; Pascoe et al., 2018; Robertson et al., 1997; Unsworth et al., 2022; Unsworth & Robison, 2020). In Chapter 2, we asked participants to rate their motivation after each block of the complex span task to test whether the relationship between WMC and sustained attention is moderated by ***resource depletion*** (decreased attention performance due to exceeding WMC; Helton & Russell, 2013) or ***mindlessness*** (unwilling task engagement due to low intrinsic motivation; Manly, 1999; Robertson et al., 1997). The measures used were taken from the intrinsic motivation inventory (McAuley et al., 1989; Ryan, 1982) and prompted participants to self-report their ***effort*** ("I tried very hard to do well in this part of the task."), ***perceived competence*** ("I think I did pretty well in this part of the task."), and ***interest*** ("This part of the task was fun to do.") on a 7-point Likert scale.

1.3 Working Memory and Sustained Attention

It is important to understand the relationship between WMC and sustained attention and how they contribute to complex cognition, however, this relationship is not yet fully understood. In terms of WM and sustained attention, prior research has shown that individual differences in WMC are associated with individual differences in sustained attention. People who have lower WMC demonstrate worse performance in sustained attention tasks than people with higher WMC (Adam & deBettencourt, 2019; McVay & Kane, 2009; Unsworth et al., 2010; Unsworth, Robison, et al., 2021a; Unsworth & Robison, 2020; Unsworth & Spillers, 2010). In other words, WMC is related to attention fluctuations, lapses of attention and mind wandering. For example, Unsworth et al. (2010) reported that longer RTs and τ in a sustained attention task (PVT) were related to performance on a complex span task. In addition, McVay and Kane (2009) reported that in the SART task, individuals with low WMC had lower accuracy and longer RT variability than individuals with high WMC. Furthermore, individuals with low WMC experienced more mind-wandering (McVay & Kane, 2009, 2012; Unsworth & Robison, 2016). These findings suggests that individual differences in WMC are related to many facets of sustained attention.

In addition, these findings are consistent with the attention control theory of WMC, which posits that WMC encompasses not only the storage and retrieval of information but also the ability to maintain sustained attention (Engle et al., 1999a). A notable study by McVay and Kane (2012) support for this theory. They conducted a latent variable study assessing WMC, attention control and reading comprehension and mind wandering during two reading comprehension and two attention control tasks. They found mind-wandering as a latent variable. Moreover, they demonstrated that the correlation between WMC and reading comprehension is primarily driven by differences in sustained attention, rather than by differences in WMC. In other words, individuals with higher WMC perform better in reading comprehension not because they can hold more information in memory, but because they are less prone to mind-wandering while reading, allowing them to stay focused on the text.

Although establishing the link between WMC and sustained attention, it is important to understand why they are related and under what conditions the relationship is strongest. The resource depletion theory (Caggiano & Parasuraman, 2004; Helton & Russell, 2011) and the mindlessness theory (Manly, 1999; Robertson et al., 1997) may provide some evidence when they are related. According to the resource depletion theory, tasks requiring high WM demands may deplete attentional resources over time, thereby leading to poorer sustained attention. Caggiano and Parasuraman (2004) used a dual-task approach. Participants concurrently performed WM tasks, alongside a spatial sustained attention task for 20 minutes. Results revealed that performance in the sustained attention task declined over time only when participants concurrently engaged in the WM task, whereas there was no such decrement in sustained attention when it was not coupled with a working memory load. In addition, Helton and Russel (2011) examined how simultaneous verbal and spatial working memory demands influence performance in a sustained attention task involving target detection. In this study, participants engaged in a target detection task while concurrently performing either a spatial or a verbal working memory task, or they performed control tasks with no memory load. The decline in sustained attention performance, indexed by longer RTs and reduced detection to target stimuli as time progressed, was exacerbated when participants concurrently engaged in both spatial and verbal WM tasks.

In addition, it is important to understand whether the relationship between sustained attention and WMC changes depending on the duration of engagement in WM tasks. The resource depletion theory suggests that sustained attention performance decreases over time because attentional resources become depleted with prolonged task engagement. According to this theory, time-on-task effect is a factor underlying why individuals have difficulty to maintain attention. Investigating this relationship could provide information about the underlying mechanisms of sustained attention and its interaction with working memory processes. For instance, if sustained attention declines more rapidly with longer durations of WM task engagement, it would support the resource depletion theory. However, to my knowledge, no study has specifically examined how the relationship between sustained attention and WMC is influenced by the duration of engagement in WM tasks.

In contrast to the resource depletion theory, there are studies indicating that reducing the load on WM results in diminished sustained attention (Levinson et al., 2012; Unsworth & Robison, 2016). Unsworth and Robison (2016) investigated the impact of lapses of attention on measures of WMC. Participants engaged in change detection task as a WM task while indicating whether they were focused on the task or experiencing mind-wandering. In this study, participants were prompted during a WM task to indicate whether they were focused on the task or experiencing mind wandering. Results showed that participants experienced almost the same mind-wandering scores across all set sizes, referring to the number of items to be remembered in a given trial. (Set size 1 M = .27, SD = .24; Set size 4 M = .26, SD = .25; Set Size 8 M = .27, SD = .24) and no significant differences in mind-wandering scores were found amongst all set sizes, indicating that the resource depletion theory was not supported. Similarly, Levison et al. (2012) reported that there was a positive relationship between WMC and sustained attention during undemanding task. Individuals with higher WMC reported experiencing more task-unrelated thoughts during undemanding tasks. These findings challenge the resource depletion theory, and it is still unclear whether resource depletion explain why WMC is related to sustained attention.

In parallel with these findings, the mindlessness theory (Manly, 1999; Robertson et al., 1997) may provide an alternative explanation for lapses of attention in WM during low set sizes or the positive relationship between sustained attention and WMC. This theory suggests that failures in sustained attention occur due to under-stimulation, task monotony, and boredom. When participants find the task easy, uninterest, or monotonous, individuals who exert lower effort may have difficulty in sustaining attention. Indeed, some studies found that participants with lower levels of intrinsic motivation showed poorer sustained attention (Seli et al., 2015; Unsworth, Robison, et al., 2021a; Unsworth & Robison, 2020). Furthermore, as WM load increases, individuals may perceive a decrease in their competence, potentially strengthening the association between WM and sustained attention. The link between sustained attention and working memory might not arise from individuals depleting their resources at high WM loads, rather, it could be attributed to a reduced intrinsic motivation to engage in the task. Taken together, it is still unclear under which circumstances the relationship between WM and sustained attention is stronger. More importantly, to the best of our knowledge, the moderating effects of different working memory set sizes and intrinsic motivation on the relationship between WM and sustained attention have not been jointly examined.

Furthermore, sustained attention and WMC may explain the relationship between WMC and fluid intelligence accounting for attention control. The maintenance and disengagement theory (Engle, 2018; Shipstead et al., 2016) proposed the relationship between WMC and fluid intelligence is due to individual differences in attention control mechanism. However, Rey-Mermet et al. (2019) did not support the theory and they found attention control did not mediate the relationship between WMC and fluid intelligence. These unclear results raise the question of how attention control is measured. According to the maintenance and disengagement theory, sustained attention as a component of attention control is responsible for the maintenance of information in WM. However, sustained attention also involves automatic or more fundamental processes focused on maintaining attention with high level readiness to respond to stimuli, especially when measured through simple RT and psychomotor vigilance task (PVT), which do not necessarily include inhibitory control or rare target detection tasks. Unsworth et al. (2010) found that longer RTs and greater RT variability in the simple RT task were related to WMC and fluid intelligence. This suggests that individuals who are more vigilant are better performance in WMC and fluid intelligence task. In addition, lapses of attention result in failures in goal maintenance, or goal neglect (McVay & Kane, 2009), which could lead to both lower WMC and fluid intelligence performance above and beyond attention control. Therefore, to the best of our knowledge, it remains unclear whether sustained attention, distinguished from attention control, contributes to the relationship between WMC and fluid intelligence.

1.4 Aims of the Thesis

The thesis has three main goals. The first aim of the thesis is to investigate the relationship between individual differences in WMC and individual differences in sustained attention and the factors that increase or decrease the strength of the association between WMC and sustained attention. The second aim of thesis is to assess whether sustained attention and attention control are the same construct or distinct. If sustained attention and attention control are distinct, the third aim of thesis is to investigate whether sustained attention mediates the relationship between WM and fluid intelligence above and beyond attention control.

Chapter 2, will test the resource depletion theory (Caggiano & Parasuraman, 2004; Head & Helton, 2014) and the mindlessness theory accompanied by intrinsic motivation. Therefore, we will investigate whether there is the moderation effect of set size in WMC, time-on-task effect during WM task, and intrinsic motivation on the relationship between WMC and sustained attention. To address this aim, the relationship between WMC and sustained attention will be investigated under different set sizes (set size 3 and set size 6; participants might be asked to remember either 3 items or 6 items) and in the first and second half of the time spent in WM task. In addition, after each condition, participants' intrinsic motivation levels will be asked. If the resource depletion theory is correct, a stronger relationship would be expected under conditions presented in set size 6 and in the second half of the task. Higher set sizes require more use of WMC to maintain and manipulate information, leading to greater depletion of these resources over time. Individuals with low WMC would likely exhibit poor sustained attention performance in set size 6. Conversely, if the mindlessness theory, accompanied by intrinsic motivation, is correct, we would expect a moderated effect of set size and intrinsic motivation. When tasks are easy, individuals with lower intrinsic motivation may invest less effort or find the task less interesting, leading to a stronger relationship between sustained attention and working memory capacity for these individuals.

In chapter 3, confirmatory factor analysis will be employed to examine whether sustained attention and attention control are different constructs. To address this aim, we will use a latent variable modelling including three sustained attention tasks without any distractions and three attention control tasks. If they are found to be different constructs, mediation analysis will then be conducted to investigate whether sustained attention may explain the relationship between fluid intelligence and WM.

CHAPTER 2 – Working Memory and Sustained Attention: An individual differences study examining the role of task-specific and motivational factors

Contributions:

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Conference presentation from this chapter:

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Abstract

Working memory capacity (WMC) and sustained attention are related. Explanations for this association predominantly focus on resource depletion, assuming that overloading WMC leads to lapses of attention. The present individual-differences study explored mindlessness as an alternative explanation proposing that lower motivation reduces sustained attention. Thus, this study aimed to investigate when and under what circumstances the relationship between WMC and sustained attention is more pronounced. N = 267 participants completed a complex span task with varying task demands and a simple reaction time task to measure WMC and lapses of attention, respectively. After each block of the complex span task, participants self-reported their intrinsic motivation (enjoyment, effort, and perceived competence). Need for cognition was assessed to account for trait motivation. Results confirmed that poorer WMC was associated with more attention fluctuations in set size 3. Moreover, effort and set size moderated the relationship between WMC task and sustained attention. Thus, the results are consistent with a mindlessness explanation with motivation conceptualised as effort. Furthermore, we found that participants reported significantly lower intrinsic motivation under high WMC task demands, suggesting that individual differences in intrinsic motivation may explain past findings of increased lapses of attention after resource depletion.

2.1 Introduction

Working memory (WM) is a limited-capacity system that temporarily maintains and manipulates information according to the task goals (Engle, 2002, Mashburn et al., 2020). Individual differences in WM capacity (WMC) have been shown to be strongly related to individual differences in attentional control (Engle & Kane, 2004; Kane et al., 2007; for a meta-analysis, see Unsworth et al., 2021). Attentional control refers to the ability to sustain an operative goal and relevant information despite potential distractions. These distractions can arise from the external environment, internal thoughts or self-generated information, and habitual tendencies (von Bastian et al., 2020). The attention control theory (Engle, 2002; Engle & Kane, 2004) posits that this strong relation between WM and attentional control exists because they are both necessary for the ongoing information processing and subsequent actions, and tap the same domain-general attentional ability. These two constructs fundamentally require the ability to sustain attention in order to maintain goal-relevant information (Engle & Kane, 2004). Therefore, the attention control theory of WMC suggests that sustained attention, assumed to be an important aspect of attentional control, is associated with WMC. Understanding the relationship between WMC and sustained attention is important because both play critical roles in our daily activities and moments of wakefulness.

Sustained attention (also referred to as vigilant attention or vigilance) refers to consistently maintaining attention to a single task, event or object for a prolonged period of time prioritizing it over other stimuli (Langner & Eickhoff, 2013; Mackworth, 1948; Tsukahara & Engle, 2023). Maintaining attention on a single task, whether it's listening to a lecture as a student or monitoring air traffic as a radar operator, is challenging even for short periods, spanning from seconds to minutes (Mackworth, 1948). This difficulty may arise because attention tends to fluctuate, lapse, or be captured by environmental distractions or self-generated thoughts.

Sustained attention is prone to attentional fluctuation and lapses, particularly in the presence of internal or external distractions. For instance, during WM tasks, fluctuations or lapses in attention can impair the active maintenance and regulation of information, affecting the efficiency of WMC, and leading to potential performance decrements or errors (Helton & Russell, 2013; Unsworth & Robison, 2016). Typically, fluctuations in attention are assessed through intra-individual variability in reaction times (RTs), and lapses of attention are indexed by prolonged RTs. Previous research typically assessed intra-individual variability in RTs, indexed by standard deviation of RTs (SD_{RT}), with tasks such as the continuous performance task (CPT), and sustained attention to response task (SART). These tasks require mostly responding to target stimuli (90%) and inhibiting rare non-target stimuli (10%). Larger moment-to-moment deviations from the mean RT reflect greater inconsistency in reacting to stimuli, indicating attention fluctuations (see Esterman & Rothlein, 2019; Robertson et al., 1997).

Lapses of attention are typically measured with tasks such simple reaction time task (Simple RT) and the psychomotor vigilance task (PVT). In these tasks, participants are asked to respond to each stimulus as quickly as possible by pressing the button. In trials where participants are highly focused on the current task, RTs will be short. However, on other trials, participants may experience a lapse, resulting in longer RTs (Unsworth, Robison, et al., 2021b). The τ parameter, which is obtained from fitting an Ex-gaussian function to the overall RT distribution, represents the long tail of the distribution and is, therefore, useful to assess lapses of attention (Unsworth et al., 2010).

2.1.1 Why are WMC and sustained attention related?

Previous research has shown that individual differences in WMC and individual differences in sustained attention are correlated with each other (McVay & Kane, 2009; Redick, 2014; Unsworth et al., 2010; Unsworth & Robison, 2016, 2020; Unsworth, Miller, & Robison, 2021; Unsworth & Spillers, 2010). That is, people with higher WMC show better performance in sustained attention tasks, experience fewer attention fluctuations, and have fewer lapses of attention compared to those with lower WMC. For example, McVay and Kane (2012) reported that individuals with higher WMC performed better in a reading comprehension task because they were less prone to mentally drift away from the task and better able to sustain their attention while reading. Based on these findings, it has been argued that WM highly overlaps with sustained attention (Engle, 2018), and that these two abilities share the same attentional resource.

Two key theoretical explanations have been put forward for why individuals find it challenging to maintain focus on a task, and why WMC may be related to sustained attention: resource depletion (Caggiano & Parasuraman, 2004), and the mindlessness (Manly, 1999; Robertson et al., 1997).

2.1.1.1 Resource Depletion

The resource depletion theory of sustained attention posits that individuals have a limited capacity for their information processing and sustained attention uses the available resource that can be depleted in the limited system when they are continuously used. According to this theory, sustained attention tasks such as simple RT tasks or CPT are taxing and demanding in terms of effort (Caggiano & Parasuraman, 2004; Warm et al., 2008; Warm & Dember, 1998). In addition, the ability to sustain attention typically declines with time on task (Lim & Dinges, 2008; Unsworth et al., 2010). Resource depletion theory proposes that over time, the continuous demand of the information processing in sustained attention tasks gradually diminishes the limited attentional resources that cannot be replenished, resulting in decreased vigilance (Hancock, 2017; Head & Helton, 2014; Helton et al., 2005; Helton & Warm, 2008), which is also called time-on task effect.

There is not only correlational but also experimental evidence that WM and sustained attention share a common resource. Caggiano and Parasuraman (2004) showed that performance in sustained attention tasks is significantly influenced by concurrent WM load. Participants engaged in a WM task concurrently with a sustained attention task. In their study, they found that concurrent WM load reduced performance in sustained attention task relative to no WM load. This suggests that the relationship between them was due to attention as a shared resource, thereby decreased efficiency of attentional control, depending on task demands. In addition, Helton and Russel (2011) investigated the impact of concurrent verbal and spatial WM demands on performance in a sustained attention task. They examined performance in a letter detection vigilance task where participants detected rare or infrequent target stimuli as the task progresses. Participants completed this task under different conditions: with verbal or spatial WM load and in control conditions where no memory load was present during the task. In each experiment, participants were randomly assigned to either a working memory condition, where they had to retain letters or a dot pattern during the vigilance task, or a control condition where no such memory retention was required. Helton and Russell (2011, 2013) found that both verbal and spatial WM load exacerbated sustained attention performance, indicating that these tasks utilize common attention resources regardless of the materials, supporting a domain-general conceptualisation of sustained attention. Based on these studies, resource depletion theory suggests that the relationship between WM and sustained attention can be explained by the shared utilization of attentional resources. As individuals engage in tasks requiring significant cognitive effort, such as maintaining information in WM, their attentional resources become depleted over time, leading to a decline in sustained attention performance. However, these three studies address how sustained attention performance is affected by WM load, but they do not examine how sustained attention changes as resources are depleted over time.

However, evidence from studies investigating mind-wandering, which means the shift or fluctuations of attention away from a primary task to the task unrelated information or internal thoughts or goals (Mrazek et al., 2012; Smallwood & Schooler, 2006), contradicts this notion of resource depletion. Specifically, studies have shown that reducing load in WM may increase instances of mind-wandering (Baird et al., 2012; Levinson et al., 2012; Rummel & Boywitt, 2014; Unsworth & Robison, 2016), suggesting better sustained attention when WM demands are high. For example, Unsworth and Robison (2016) provided some evidence about mind-wandering did not only occur when WM task was difficult. They observed that participants reported mind wandering during 27% of completing a WM task, even when WM load was low. This finding has indirectly cast doubt resource depletion. Moreover, Levison et al. (2012) found that taxing WM consistently reduced mind wandering. Individuals with greater WMC reported experienced more task-unrelated thoughts during undemanding tasks. Furthermore, Rummel and Boywitt (2014) manipulated the demands of the n-back task by including both 1-back and 3-back conditions. In this task, participants were presented with a sequence of letters and asked to indicate whether the current stimulus matched the one presented one or three steps earlier in the sequence. Thought probes were employed to determine whether participants were focusing on the current task or unrelated task information during the n-back task. The study found that high WMC individuals reported more unrelated thoughts under low WM load compared to those with low WMC, suggesting task engagement and sustained attention increases in more attention-demanding situations rather than depleting resources.

Taken together, inconsistencies in findings regarding the relationship between WMC and sustained attention under varying WM load raise questions about the mechanism underpinning the relationship between them. Specifically, it remains unclear whether this relationship occurs under conditions of low WM load or high WM load. Furthermore, all previous studies did not examine whether the relationship between WMC and sustained attention have changed over time (e.g., the first half of WM task or the second half of the WM). Moreover, previous mind wandering studies predominantly rely on self-reports, thus lacking information from behavioural measurements and capturing only one aspect of sustained attention. These studies did not account for fluctuations in attention and lapses of attention (e.g., longer RTs), which are other critical components of sustained attention. Consequently, it is still unknown how sustained attention is behaviourally related to WMC under varying WM load. Despite the valuable insights provided by existing studies, such as those examining sustained attention and its association with WMC, to my knowledge, no research to date has systematically investigated the interaction between fluctuations in attention and lapses of attention and WMC performance under different WM load conditions (task difficulty) and time-on-task conditions.

2.1.1.2 Mindlessness

In contrast to the resource depletion theory, the mindlessness theory (Manly, 1999; Robertson et al., 1997) proposes that failures in sustained attention tasks arise from the withdrawal of focused attention from the task due to monotony or boredom (Scerbo, 1998). Manly et al. (1999) employed two variations of the sustained attention-to-response task (SART) to explore the monotony of the task. In the SART, participants are typically presented with a continuous stream of stimuli, often numbers or letters, and are instructed to respond to each stimulus as quickly as possible, except for a specific target stimulus. This target stimulus is infrequently presented within the stream, and participants are instructed to withhold their response when it appears. In one version, participants were instructed to withhold responses to infrequent target stimuli (11%) – rendering this a highly monotonous task –, while in the other version, participants were instructed to withhold responses to frequent (50%) targets. Manly et al. found poorer performance in the more monotonous condition. Hence, in boring situations, where responses become more automatic, and the target stimuli are exceedingly rare and require less attentional control, attention may drift away from the primary task, resulting in decreases in sustained attention performance.

Mindlessness accounts are consistent with the notion that WM tasks, particularly in low load conditions, may also be perceived as uninteresting, resulting in lower intrinsic motivation levels. Many studies have reported that individual differences in sustained attention are related to self-reported intrinsic motivation (Robison & Unsworth, 2015, 2018; Seli et al., 2015; Unsworth, Robison, et al., 2021b; Unsworth & McMillan, 2013; Unsworth & Robison, 2020). Individuals with high intrinsic motivation levels are less likely to experience attention fluctuations and lapses of attention. This is because when individuals are intrinsically motivated, they are more likely to exert effort or engage in the task, and to persist internal or external distractions.

Studies found that levels of intrinsic motivation were positively associated with sustained attention. Consistently, however, past studies reported no or only weak correlations between intrinsic motivation and WMC (Robison & Unsworth, 2015, 2018; Unsworth, Robison, et al., 2021b; Unsworth & McMillan, 2013; Unsworth & Robison, 2020). Moreover, Unsworth and Robison (2020) reported that intrinsic motivation did not mediate the relationship between WMC and sustained attention. However, these studies investigated how WMC and intrinsic motivation affected individual differences in sustained attention; therefore, these past studies solely measured intrinsic motivation in sustained attention tasks, not in WM tasks. They examined how intrinsic motivation such as effort, interest, or enjoyment influenced sustained attention performance. However, what these studies did not directly assess was the role of intrinsic motivation within WM tasks. WM tasks involve relatively different task difficulty levels and may reveal distinct motivational levels compared to sustained attention tasks. The absence of a correlation between WMC and intrinsic motivation in previous studies may be explained by the fact that intrinsic motivation was exclusively measured within sustained attention tasks, while its role within WM tasks was not directly examined. Therefore, it is not surprising that they did not find a correlation between WMC and intrinsic motivation, given the different cognitive demands and motivational dynamics inherent in each task type. Thus, understanding the interplay between intrinsic motivation and WM performance can provide valuable information about the relationship between WMC and sustained attention, that is, intrinsic motivation depending on WM tasks may strengthen or diminish the relationship between sustained attention and WMC.

Taken together, the precise conditions under which the relationship between sustained attention and WMC emerge remain unclear and it is unknown to what extent this relationship is influenced by the duration of time spent on task, WM load, and by individual differences in intrinsic motivation levels.

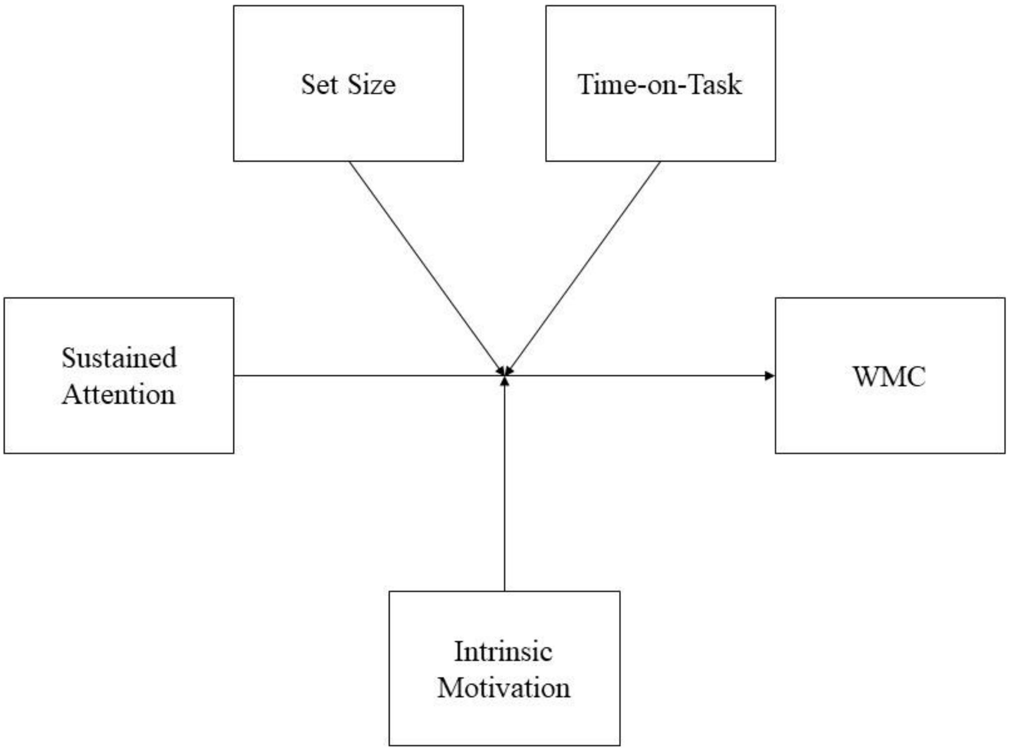
2.1.2 The Present Study

The main goal of the current study was test these two competing theories by investigating under what circumstances (task difficulty: low load vs high load; time-on- task: the first half vs the second half) and for whom (individual differences in intrinsic motivation) the relationship between sustained attention and WMC is strongest. For this purpose, the present study used a combined experimental and correlational approach. Participants performed a complex span task, with task difficulty manipulated by using two set sizes: set size 3 and set size 6. Time-on-task was examined by dividing the complex span task into two halves: the first half and the second half. Each participant completed four blocks in a certain order: set size 3, set size 6 (first half), set size 6 and set size 3 (second half). After each block, participants reported their intrinsic (state) motivation levels, assessing aspects of effort, perceived competence, and enjoyment. The need for cognition, a trait reflecting individuals' tendency to engage in complex cognitive activities, was also examined as a covariate to control for trait motivation.

Resource depletion theory predicts that the correlation between WMC and sustained attention should be stronger when task difficult is high (i.e., in the set size 6 condition) and time on task is longer (i.e., during the second half of the task). This prediction arises from the assumption that sustained attention and WMC share common cognitive resources, which are expected to deplete as a result of increased task difficulty and prolonged time-on-task. In contrast, mindlessness theory assumes that individuals with higher fluctuations and lapses of attention show lower WM performance because they are less intrinsically motivated. They may find the WM task uninteresting, perceive themselves as less competent, and/or exert less effort. For example, when the WM task is easy, individuals may still find it uninteresting if it fails to engage their attention or challenge their cognitive abilities. However, they may perceive themselves as more competent and exert less effort compared to when the task is difficult. Hence, the association between sustained attention and WMC is predicted to be stronger in the set size 3 condition due to intrinsic motivational factors such as higher perceived competence, lower effort and/or lower interest. Hence, to test these hypotheses, the moderation effects of task difficulty, time-on-task effects, and intrinsic motivation on the association between WMC and sustained attention were examined (see Figure 2.1).

Figure 2.1

Hypothesised moderation model.



Note. The moderation model tested two theories: resource depletion vs mindlessness. If resource depletion is correct, *increasing* the set size (i.e. set size 6) and time on task (i.e. second half of the task) would strengthen the relationship between sustained attention and WMC, regardless of intrinsic motivation. If mindlessness is correct, *decreasing* the set size (i.e. set size 3) and time on task (i.e. first half of the task), and low intrinsic motivation (effort, perceived competence and interest) would strengthen the relationship between sustained attention and WMC. Set size = 3 vs 6; time-on-task effect = first half vs second half; WMC = working memory capacity.

2.2 Method

2.2.1 Participants

A total of 267 participants took part in this study. The initial sample comprised 93 men, 173 women, and 1 non-binary person, with an age *M* = 23.57 years (*SD* = 5.28 years; range 18 to 35 years). The final sample after data cleaning and outlier detection consisted of 249 participants, including 162 women with an age *M* = 22.97 years (*SD* = 5.04), 86 men with an age *M* = 24.29 years (*SD* = 5.38), and 1 non-binary person. Participants were recruited from the participant pool of the University of Sheffield and through local poster advertisements in Sheffield and on social media. Participants received financial compensation for the study with either a £20 Amazon UK voucher or ten course credits. Ethics approval was obtained from the University of Sheffield Research Ethics Committee for this study.

2.2.2 Procedure and Materials

The present study was a part of a collaborative research study consisting of a 15-min home questionnaire session and a laboratory session. The laboratory session for the whole study lasted about 2 hours. The present study consisted of home questionnaires and data from the third and fourth tasks of the laboratory session. After signing a consent form, all participants completed two questionnaires, a demographic background questionnaire and the Need for Cognition Scale (NFC; Cacioppo & Petty, 1982), via a link from Qualtrics Survey before the laboratory assessment. In the laboratory session, participants were tested in groups of up to 7 in a group research room divided by partitions. They completed a numerical complex span task measuring WMC, three questions from the Intrinsic Motivation Inventory (IMI; McAuley et al., 1989; Ryan, 1982), and a simple reaction time task (Simple RT) measuring sustained attention. Task were administered with Tatool Web, an open-source experiment software (www.tatool-web.com: von Bastian et al., 2013).

2.2.2.1 Numerical Complex Span Task

The task was modelled by von Bastian and Eschen (2016) after the task of Daneman and Carpenter (1980) and Conway and colleagues (2005). In this task, participants were asked to memorise numbers in a sequentially presented order. The presentation of memoranda was interleaved with a secondary task. Numbers (1 to 9) were presented for memorisation at a rate of 1 s each. In between each of these numbers, participants had to decide as quickly and as accurately as possible whether a digit was smaller than 5 (e.g., ‘2’) or greater than 5 (e.g., ‘7’). After sets of 3 or 6 numbers, participants were asked to recall the numbers in correct serial order. Participants had unlimited time to recall the digits. Before starting the task, participants completed four practice trials to familiarise themselves with the task.

2.2.2.2 Intrinsic Motivation Questions:

Following each block of the numerical complex span task, participants were asked to indicate their intrinsic motivation level on a 7-point scale adapted from the Intrinsic Motivation Inventory (IMI; McAuley et al., 1989; Ryan, 1982). Three statements that show how participants were motivated while performing the blocks of numerical complex span tasks were adapted from the IMI. Listed below are the statements related to each dimension of motivation:

1. **Effort**: "I tried very hard to do well in this part of the task.” this statement assesses the level of effort participants put into the task. It reflects their self-reported exertion and engagement in trying to perform well.
2. **Perceived Competence**: "I think I did pretty well in this part of the task." this statement assesses participants' thoughts of their own competence in the task. It captures their subjective evaluation of how well they believe they performed.

3. **Interest/Enjoyment**: "This part of the task was fun to do." this statement measures the participants' level of interest and enjoyment during the task. It reflects the subjective experience of finding the task enjoyable or interesting.

These statements provide insights into participants' intrinsic motivation, measuring factors such as effort, perceived competence, and the enjoyment or interest they derived from the numerical complex span task.

2.2.2.3 Simple RT Task

The simple RT task was used to measure sustained attention. Participants were presented with single digits (1 to 9) on the screen. Participants were asked to press the space key on a computer keyboard as quickly as possible once a number appeared on the screen. Stimuli were randomised. Interstimulus intervals (ISI) randomly ranged from 1 s to 10 s. Each participant performed the entire task for 10 min. We assessed two aspects of sustained attention: attention fluctuations and lapses of attention. The dependent variable to measure attention fluctuations was SD_{RT}, with a higher SD_{RT} indicating greater intra-individual variability in RTs. The dependent variable to assess lapses of attention was the τ parameter estimated from fitting an Ex-gaussian function to the RT distribution. A higher τ value reflects a more gradual decline of the exponential component of the RT distribution, leading to a distribution characterized by an extended right tail that reflects more slower responses.

2.2.2.4 Need for Cognition Scale (NFC)

The 18-items NFC was used to measure the tendency to what extent an individual engages in a cognitive task and enjoys thinking (Cronbach's $\alpha = 0.83$). Participants indicated whether the statement is characteristic of them on a 5-point scale (1 = extremely uncharacteristic of me, 5 = extremely characteristic of me). The questionnaire was administered using a computer and as a dependent variable, the mean score was computed.

2.3 Results

All statistical analyses were performed using RStudio version 4.2.2 (R Core Team, 2020). Prior to analysis, all variables were *z*-standardized. First, a zero-order correlation analysis was conducted to examine the relationship among all variables within each condition, with a particular focus on the relationship between sustained attention (SD_{RT} and τ), WMC, intrinsic motivation in the two task difficulty conditions (set size 3 and set size 6), and time on task (first half and second half). Next, a multiple regression was conducted to test the moderation effects of task difficulty, time-on-task, and intrinsic motivation on the relationship between sustained attention and WMC, while accounting for NFC.

According to Schönbrodt and Perugini (2013) obtaining reliable estimates for correlation analysis requires a sample size of approximately 250 to achieve sufficient statistical power. Therefore, the sample size of the current study consisted of 267 participants. However, 11 participants were excluded from the dataset because they demonstrated an accuracy below 75% in secondary task in the numerical complex span (i.e., judging whether a number was smaller or greater than five), indicating they did not fully engage with the secondary task. Low accuracy on this part also suggests that participants may have been able to effectively employ rehearsal and chunking strategies to aid memory recall. In addition, Mahalanobis distance was computed to detect multivariate outliers with the Routliers package (Leys et al., 2019). As a result of this analysis, 7 participants with multivariate outliers (approximately 3% of the original sample), were removed from the dataset. Finally, in the simple RT task, trials with an RT< 100 ms were excluded from the analysis of the simple RT task. Table 2.1 presents the descriptive statistics of all included measures.

Table 2.1

Descriptive statistics for all measures (mean, standard deviations, median, minimum, maximum values)

Measures	*M*	*SD*	*Median*	*Min*	*Max*
WMC	.82	.20	.88	.11	1
Set size 6	.78	.22	.85	.10	1
Set size 3	.90	.18	1	.12	1
First half of task	.82	.21	.88	.11	1
Second half of task	.82	.20	.88	.11	1
Effort	5.75	1.33	5.96	1.25	7
Set size 6	5.89	1.27	6	1	7
Set size 3	5.60	1.53	6	1	7
First half of task	5.81	1.38	6	1	7
Second half of task	5.68	1.43	6	1	7
Perceived Competence	4.88	1.25	5	1	7
Set size 6	4.37	1.49	4.5	1	7
Set size 3	5.39	1.26	5.5	1	7
First half of task	4.75	1.40	5	1	7
Second half of task	5.02	1.32	5.5	1	7
Interest	5.28	1.44	5.5	1	7
Set size 6	5.10	1.61	5.5	1	7
Set size 3	5.45	1.40	6	1	7
First half of task	5.33	1.46	5.5	1	7
Second half of task	5.22	1.52	5.5	1	7
NFC	3.34	.53	3.33	1.16	4.88
Sustained Attention					
τ	92.36	64.49	78.13	20.02	547.00
SD_{RT}	122.95	114.08	91.29	30.09	1070.99

Note. WMC = working memory capacity; NFC = need for cognition; τ = tau parameter obtained from Ex-Gaussian; SD_{RT} = standard deviation of reaction time. WMC was accuracy. Effort, perceived competence and interest scaled from 1 to 7. NFC was the mean of self-reported scores.

Table 2.2 lists Pearson's correlation analyses for all variables separately for set size 3 and set size 6 as well as the first half and second half of the WM task. SD_{RT} and τ were highly correlated, $r(247) = .93$, $p < .001$. This strong correlation indicates that both measures capture a common sustained attention construct. Regarding the relationship between general WMC and sustained attention, participants with fewer lapses of attention showed higher WMC, as indicated by negative correlations between WMC and τ, $r(247) = -.14$, $p =.026$. However, WMC was not related to fluctuations in attention, as indexed by SD_{RT}, $r(247) = -.11$, $p = .081$. In addition, WMC was positively related to intrinsic motivation as state motivation, $r(247) = .42$, $p = .194$, but not with NFC as trait motivation $r(247) = .08$, $p > .05$. Specifically, WMC was highly associated with perceived competence, $r(247) = .52$, $p < .001$, and interest, $r(247) = .31$, $p < .001$, but not with effort, $r(247) = .42$, $p = .371$. Appendix A shows correlations between general WMC and intrinsic motivation with other variables regardless of the conditions.

Table 2.2

Correlation matrix among all variables for each set size and half condition separately

Measures	1.	2.	3.	4.	5.	6.	7.
				Set Size			
1. WMC	-	-.12	-.09	.09	.07	**.53*** **	**.33*** **
2. τ	**-.17** **	-	**.93*** **	-.06	-.10	.11	.00
3. SD_{RT}	**-.16***	**.93*** **	-	-.05	**-.15***	**.14***	.05
4. NFC	.05	-.06	-.05	-	.05	.04	.12
5. Effort	.09	-.09	**-.14***	.05	-	.12	.11
6. Perceived Competence	**.42*** **	-.06	-.05	**.14***	.10	-	**.54*** **
7. Interest	**.25*** **	-.05	.00	.10	.05	**.50*** **	-
				Half			
1. WMC	-	-.11	-.07	.06	.06	**.48*** **	**.32*** **
2. τ	**-.16***	-	**.93*** **	-.06	-.07	.07	-.01
3. SD_{RT}	**-.14***	**.93*** **	-	-.05	**-.13***	.09	.04
4. NFC	.10	-.06	-.05	-	.07	.06	.12
5. Effort	.06	-.11	**-.16***	.03	-	**.18** **	**.14***
6. Perceived Competence	**.52*** **	.00	.02	.12	.07	-	**.53*** **
7. Interest	**.29*** **	-.04	.01	.11	.03	**.48*** **	-

Note. Correlations above the main diagonal represent set size 6 and the second half of the task, while correlations below the main diagonal represent set size 3 and the first half of the task. Bold correlations are significant. WMC = working memory capacity; NFC = need for cognition; SD_{RT}= standard deviation of reaction time; τ = tau parameter from Ex-Gaussian. ***$p < .001$, **$p < .01$, *$p < .05$.

In the set size conditions, both sustained attention measures were negatively associated with WMC in set size 3. Individuals with lower SD_{RT} $r(247) = -.16$, $p = .014$ and τ *r*(247) = -17., *p* = .008 showed higher WMC in set size 3, but not in set size 6. Subsequently, Fisher's r to z test (Williams' *t*-test) for differences between two dependent overlapping correlations was conducted to statistically test the differences between the observed correlations. Table 2.3 lists the results of these comparisons. This analysis revealed significant differences between SD_{RT} and WMC in set size 3 compared to set size 6, $t(246) = -1.79$, $p = .037$. Although τ was found to be related to WMC in set size 3 but not in set size 6, no significant differences were observed in the correlations between τ and WMC within each condition (set size 3 and 6). Similar results were consistently found for the halves of the task. Both measures of sustained attention were related to WMC in the first half but not in the second half. Williams' *t*-test revealed that the correlation between SD_{RT} and WMC was stronger in the first half than the second half, $t(246) = -1.71$, $p = .043$. However, there were again no significant differences between τ and WMC for each half of the task. These findings indicate that the relationship between sustained attention and WMC is stronger in set size 3 and the first half of the task.

Table 2.3

Correlation comparison between WMC and sustained attention measures for each condition

Measures	WMC			
	Set Size 3	Set Size 6	*t*	*p*
τ	**-.17****	-12	-1.19	.117
SD_{RT}	**-.16***	-.09	-1.79	.037
	First Half	Second half	*t*	*p*
τ	**-.16***	-11	-1.22	.111
SD_{RT}	**-.14***	-.07	-1.71	.043

Note. Bold correlations are significant. WMC = working memory capacity; SD_{RT} = standard deviation of reaction time; τ = tau parameter from Ex-Gaussian. ***$p < .001$, **$p < .01$, *$p < .05$.

2.3.1 Moderation Analyses

Several moderation analyses were conducted to examine how set size, time-on-task, and individual differences in intrinsic motivation levels affect the strength of the relationship between sustained attention and working memory. Set size and half were represented using contrast coding. Set size 3 and the first half of the task were coded as -0.5, while set size 6 and the second half of the WM task were coded as +0.5. Finally, separate models were tested for SD_{RT} and τ because they were highly correlated but still reflecting theoretically different aspects of sustained attention. In addition, separate models were tested for effort, perceived competence, and interest, each representing different dimensions of intrinsic motivation. On the descriptive level, perceived competence decreased under challenging conditions (M = 4.37, SD = 1.49) compared to easier conditions (M = 5.39, SD = 1.26), whereas effort increased with task difficulty (M = 5.89 , SD = 1.27 for set size 6 vs M = 5.60, SD = 1.53, for set size 3). Therefore, effort, perceived competence, and interest were examined separately rather than analysing a general intrinsic motivation. NFC was included as a covariate for all models.

2.3.1.1 Sustained Attention and Effort Models

First, we examined the moderation effects of set size, time-on-task and effort on the relationship between τ and WMC after accounting for NFC. As seen in Table 2.4, significant main effects were observed for τ, b = -.11, t(979) = -3.44, p < .001, set size, b = -.55, t(979) = -9.02, p < .001, and effort, b = .08, t(979) = 2.39, p = .016, on WMC after accounting for all variables. In addition, a significant interaction between τ, set size and effort was found b = -.16, t(979) = -2.25, p = .024, suggesting that the association between τ and WMC is moderated by effort depending on set size. Figure 2.2 visualizes this three-way interaction. While effort was analysed as continuous variable, for illustration purposes only, effort levels were grouped using the 16^{th} (low effort), 50^{th} (medium effort) and 84^{th} (high effort) percentiles, following the recommendations by Hayes (2022) for skewed variables. Alternative visualisation approaches, such as plotting one standard deviation below or above the mean could exceed the observed data range. Percentiles offer greater robustness compared to mean and standard deviation measures. Specifically, the 16th and 84th percentiles are guaranteed to fall within the observed data range, regardless of the distribution shape. As illustrated in Figure 2.2, when participants reported low levels of effort, τ was negatively related to WMC in set size 3, but not in set size 6. In contrast, for medium and high effort levels, similar relationships were observed for both set sizes. In addition, the negative relationship between τ and WMC was stronger in set size 3 when effort was low compared to medium and high effort levels. This finding suggests that individuals who experience more lapses of attention had worse WM performance when the WM was easy, especially for those who reported to have exerted less effort performing the task.

Table 2.4

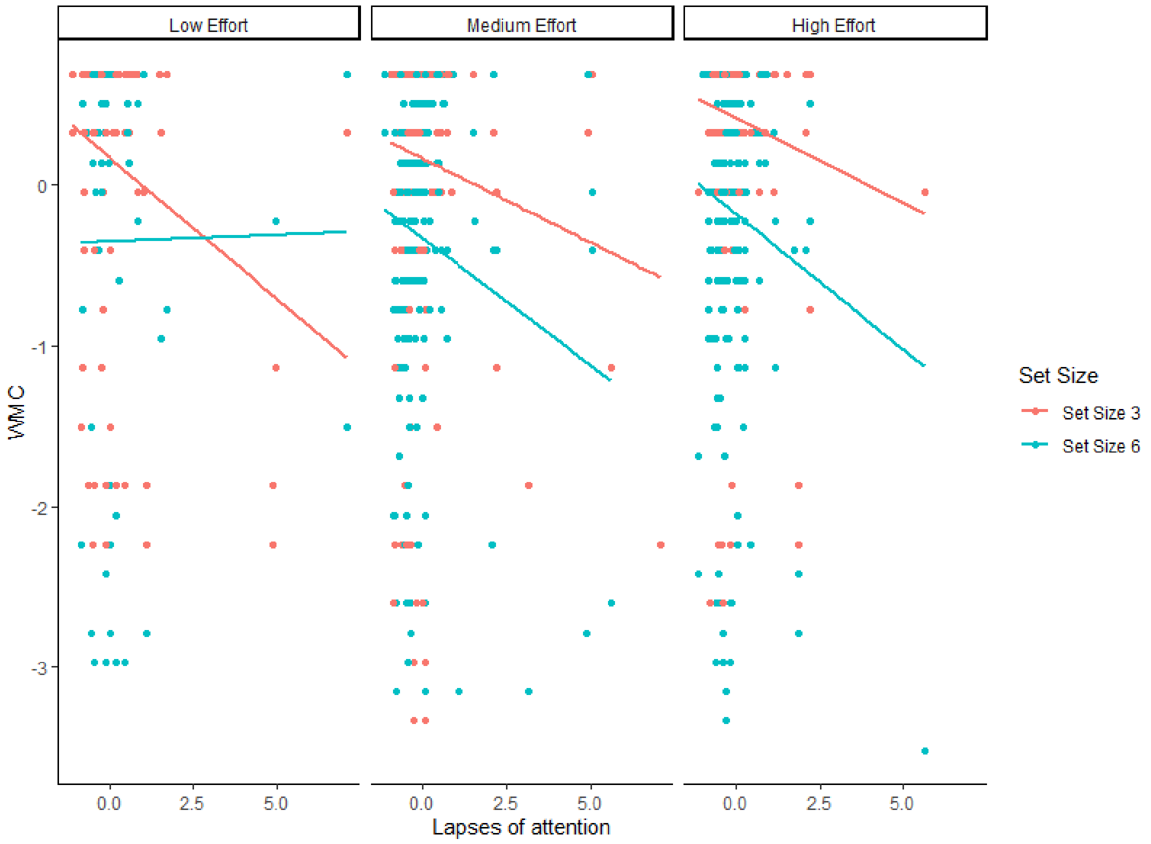
The moderation effect of set size, half and effort on the relationship between lapses of attention and WMC

Predictors	*B*	*SE*	*t*	*p*
Constant	-.00	.03	-.01	.990
τ	-.11	.03	-3.44	<.001***
Set Size	-.55	.06	-9.02	<.001***
Half	.01	.06	.28	.773
Effort	.08	.03	2.39	.016*
NFC	.06	.03	1.90	.056
τ x Set Size	.02	.07	-.33	.740
τ x Half	.04	.07	.68	.494
Set Size x Half	-.15	.12	-1.21	.224
τ x Effort	-.00	.03	-.27	.782
Set Size x Effort	.03	.06	.44	.658
Half x Effort	.02	.06	.34	.729
τ x Set Size x Half	-.06	.13	-.42	.673
τ x Set Size x Effort	-.16	.07	-2.25	.024*
τ x Half x Effort	-.09	.07	-1.27	.203
Set Size x Half x Effort	-.02	.12	-.13	.896
τ x Set Size x Half x Effort	-.07	.13	-.53	.595

Note. $F(16, 979) = 6.94$, $p < .001$, $R^2 = .10$. τ = tau parameter from Ex-Gaussian; NFC = need for cognition. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Figure 2.2

The interaction effect of τ, set size and effort on WMC



The second moderation model was conducted to investigate the relationship between SD_{RT} and WMC while also accounting for set size, time-on-task, effort and need for cognition in the model. As shown in Table 2.5, main effects were found for SD_{RT}, $b = -.12$, $t(979) = -3.22$, $p = .001$, set size, $b = -.55$, $t(979) = -8.95$, $p < .001$, and effort, $b = .07$, $t(979) = 2.36$, $p = .018$. That is, SD_{RT} and set size were negatively related to WMC, while effort was positively related to WMC when all other variables were held constant. Although no moderation effect of set size, time-on-task and effort on the relationship between attention fluctuations and WMC was found, it might be worth noting that the interaction effect between

$SD_{RT,}$ set size and effort approached significance, *b* = -.11, *t*(979) = -1.66, *p* = .096. Figure 2.3 shows the moderation effect of set size and effort on the relationship between SD_{RT} and WMC for consistency and comparability with the Figure 2.2, where we only found significant moderation effect of set size and effort on the relationship between *τ* and WMC. Additional figures showing all non-significant moderator effects on the relationship sustained attention and WMC are presented in the Appendix B and C.

Table 2.5

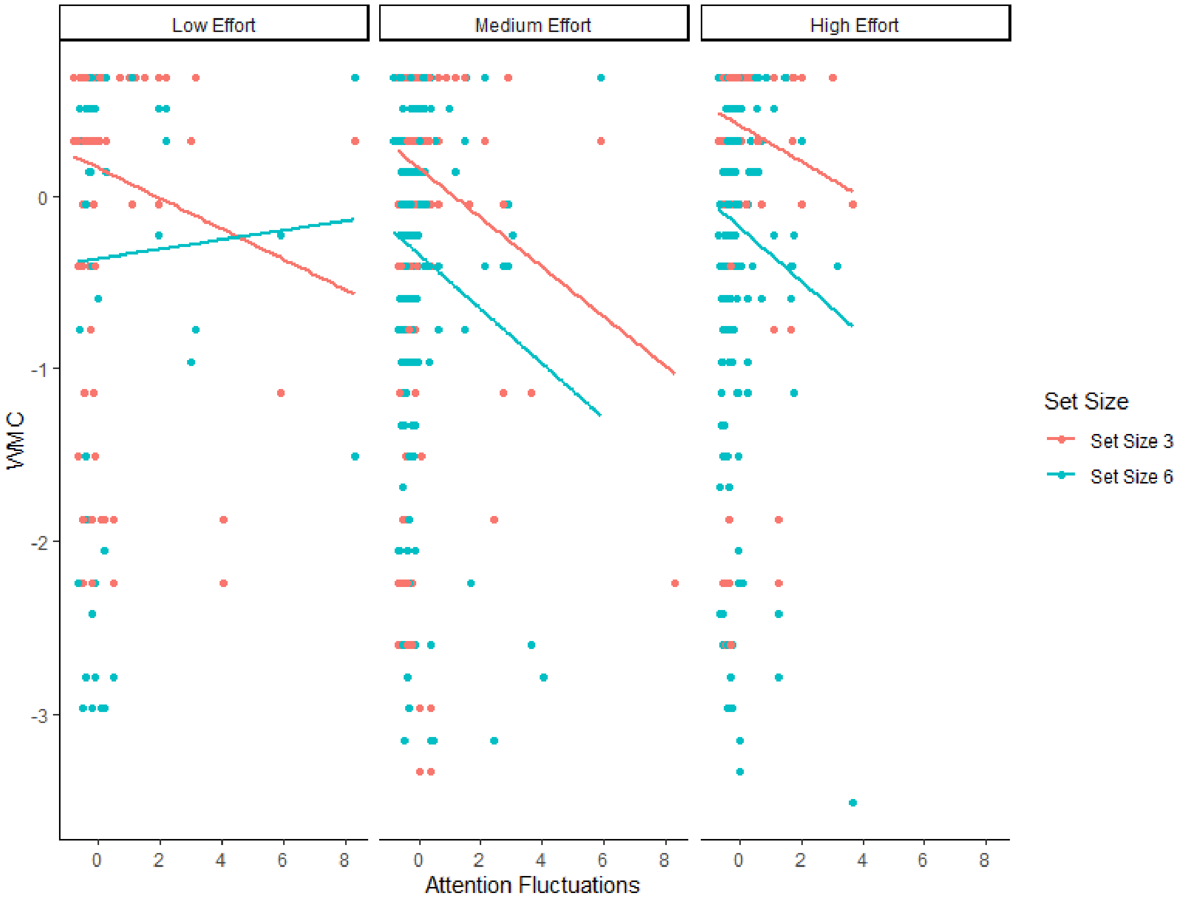
The moderation effect of set size, half and effort on the relationship between attention fluctuations and WMC

Predictors	*B*	*SE*	*t*	*p*
Constant	-.00	.03	-.21	.830
SD_{RT}	-.12	.04	-3.22	.001**
Set Size	-.55	.06	-8.95	<.001***
Half	.02	.06	.29	.766
Effort	.07	.03	2.36	.018*
NFC	.06	.03	1.94	.052
SD_{RT} x Set Size	-.00	.07	-.03	.968
SD_{RT} x Half	.05	.07	.68	.496
Set Size x Half	-.16	.12	-1.27	.204
SD_{RT} x Effort	-.05	.03	-1.61	.106
Set Size x Effort	.04	.06	.56	.569
Half x Effort	.03	.06	.43	.663
SD_{RT} x Set Size x Half	-.06	.15	-.37	.705
SD_{RT} x Set Size x Effort	-.11	.07	-1.66	.096
SD_{RT} x Half x Effort	-.06	.07	-.97	.330
Set Size x Half x Effort	-.01	.12	-.09	.923
SD_{RT} x Set Size x Half x Effort	-.11	.13	-.89	.373

Note. $F(16, 979) = 6.94$, $p < .001$, $R^2 = .10$. SD_{RT} = standard deviation of reaction time; NFC = need for cognition. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Figure 2.3

The interaction effect of SD_{RT}, set size and effort on WMC

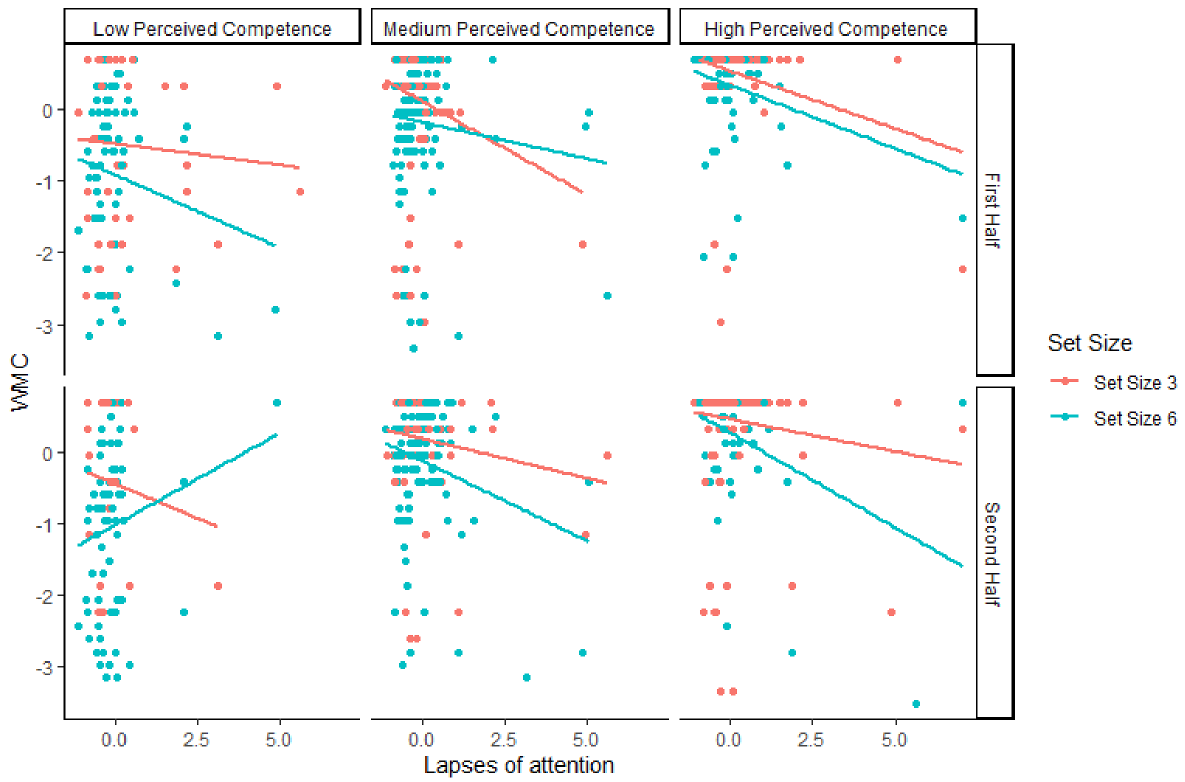


2.3.1.2 Sustained Attention and Perceived Competence Models

Moderation analysis revealed a four-way interaction. The interaction amongst τ, set size, time-on-task and perceived competence was significant, b = -.22, $t(979)$ = -2.01, p = .044, but further inspection (Figure 2.4) suggested that this significant effect was driven by a single data point in Figure 2.4 corresponding to low perceived competence, second half and set size 6. Therefore, we re-ran the analysis excluding this participant.

Figure 2.4

The interaction effect of τ, set size and perceived competence on WMC



Moderation analysis was conducted with 248 participants for perceived competence models only. For perceived competence and τ model (Table 2.6), set size and τ and were negatively associated with WMC, whereas perceived competence was positively related to WMC after accounting for the influence of the predictors. WMC was lower when set size was high, $b = -.24$, $t(975) = -4.18$, $p < .001$ and individuals experienced greater lapses of attention $b = -.16$, $t(975) = -5.41$, $p < .001$. Conversely, as individuals' perceptions of their ability to successfully complete the WM task increased, $b = .47$, $t(975) = 16.46$, $p < .001$, their WMC also increased. However, no moderating effect was found in this model (see Appendix D). Although there was no interaction effect of this relationship, the model provided some noteworthy information about WMC. The interaction effect was found only among set size, perceived competence and WMC, suggesting the relationship between WMC and perceived competence was stronger in set size 6, $b = .21$, $t(975) = 3.60$, $p < .001$.

Table 2.6

The moderation effect of set size, half and perceived competence on the relationship between lapses of attention and WMC

Predictors	*B*	*SE*	*t*	*p*
Constant	.03	.03	1.16	.244
τ	-.16	.03	-5.41	<.001***
Set Size	-.24	.06	-4.18	<.001***
Half	-.02	.06	-.26	.791
PC	.47	.03	16.46	<.001***
NFC	.03	.03	1.11	.265
τ x Set Size	-.07	.06	-1.10	.269
τ x Half	.04	.06	.60	.545
Set Size x Half	.00	.11	-.03	.969
τ x PC	-.03	.03	-.98	.324
Set Size x PC	.21	.06	3.60	<.001***
Half x PC	-.00	.06	-.09	.927
τ x Set Size x Half	-.09	.12	-.79	.427
τ x Set Size x PC	-.06	.06	-.94	.345
τ x Half x PC	-.00	.06	-.11	.910
Set Size x Half x PC	.08	.11	.70	.484
τ x Set Size x Half x PC	-.14	.12	-1.207	.227

Note. $F(16, 975) = 27.56$, $p < .01$, $R^2 = .31$. τ = tau parameter from Ex-Gaussian; PC = perceived competence; NFC = need for cognition. **p* < 0.05, ***p* < 0.01, ****p* < 0.001.

Similar to τ, SD_{RT} (Table 2.7), $b = -.16$, $t(975) = -4.82$, $p < .001$ and set size, $b = -.24$, $t(975) = -4.16$, $p < .00$ were negatively related to WMC while perceived competence, $b = .48$, $t(975) = 16.50$, $p < .001$ was positively related to WMC after accounting for the influence of the other predictors. None of the predictors moderated the relationship between attention fluctuations and WMC (see Appendix E); but, as in τ, the relationship between set size and WMC was moderated by perceived competence, $b = .21$, $t(975) = 3.60$, $p < .001$. This indicated a change in the direction of the relationship between set size and WMC as perceived competence increased.

Table 2.7

The moderation effect of set size, half and perceived competence on the relationship between attention fluctuations and WMC

Predictors	*B*	*SE*	*t*	*p*
Constant	.03	.03	1.05	.294
SD_{RT}	-.16	.03	-4.84	<.001***
Set Size	-.24	.06	-4.16	<.001***
Half	-.02	.06	-.34	.730
PC	.48	.03	16.50	<.001***
NFC	.03	.03	1.21	.224
SD_{RT} x Set Size	-.06	.07	-.99	.318
SD_{RT} x Half	.04	.07	.68	.491
Set Size x Half	-.00	.11	-.01	.987
SD_{RT} x PC	-.02	.03	-.63	.527
Set Size x PC	.21	.06	3.60	<.001***
Half x PC	-.00	.06	-.15	.877
SD_{RT} x Set Size x Half	-.04	.13	-.30	.763
SD_{RT} x Set Size x PC	-.01	.06	-.18	.852
SD_{RT} x Half x PC	.02	.06	.40	.685
Set Size x Half x PC	.07	.11	.58	.558
SD_{RT} x Set Size x Half x PC	-.15	.13	-1.18	.236

Note. $F(16, 975) = 26.97$, $p < .001$, $R^2 = .31$. SD_{RT} = standard deviation of reaction time; PC = perceived competence; NFC = need for cognition. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

2.3.1.3 Sustained Attention and Interest/Enjoyment Models

Two separate models were conducted to test whether the relationship of both τ (Table 2.8) and SD_{RT} (Table 2.9) with WMC was moderated by set size, time-on task, and interest to the task. No moderation effect was found in both models (see Appendix F and G). However, a main effect was found for τ, $b = -.12$, $t(979) = -4.14$, $p < .001$, set size, $b = -.46$, $t(979) = -7.85$, $p < .001$, and interest, $b = .27$, $t(979) = 8.97$, $p < .001$ on WMC when holding the predictors constant. Similarly, significant main effects of SD_{RT}, $b = -.12$, $t(979) = -3.70$, $p < .001$, set size, $b = -.46$, $t(979) = -7.83$, $p < .001$, and interest on WMC were also observed, $b = .27$, $t(979) = 9.13$, $p < .001$.

Table 2.8

The moderation effect of set size, half and interest on the relationship between lapses of attention and WMC

Predictors	*B*	*SE*	*t*	*p*
Constant	.00	.03	.20	.838

τ	-.12	.03	-4.14	<.001***
Set Size	-.46	.06	-7.85	<.001***
Half	.05	.06	.80	.419
Interest	.27	.03	8.97	<.001***
NFC	.03	.03	1.05	.294
τ x Set Size	.01	.06	.19	.842
τ x Half	.04	.06	.76	.447
Set Size x Half	-.13	.12	-1.06	.286
τ x Interest	-.02	.03	-.62	.535
Set Size x Interest	.11	.06	1.82	.068
Half x Interest	-.00	.06	-.01	.986
τ x Set Size x Half	-.03	.11	-.28	.777
τ x Set Size x Interest	-.03	.06	-.42	.672
τ x Half x Interest	.01	.06	.29	.788
Set Size x Half x PC	.15	.12	1.26	.205
τ x Set Size x Half x PC	-.07	.12	-.62	.530

Note. $F(16, 979) = 12.42$, $p < .001$, $R^2 = .17$. τ = tau parameter from Ex-Gaussian; PC = perceived competence; NFC = need for cognition. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table 2.9

The moderation effect of set size, half and interest on the relationship between attention fluctuations and WMC

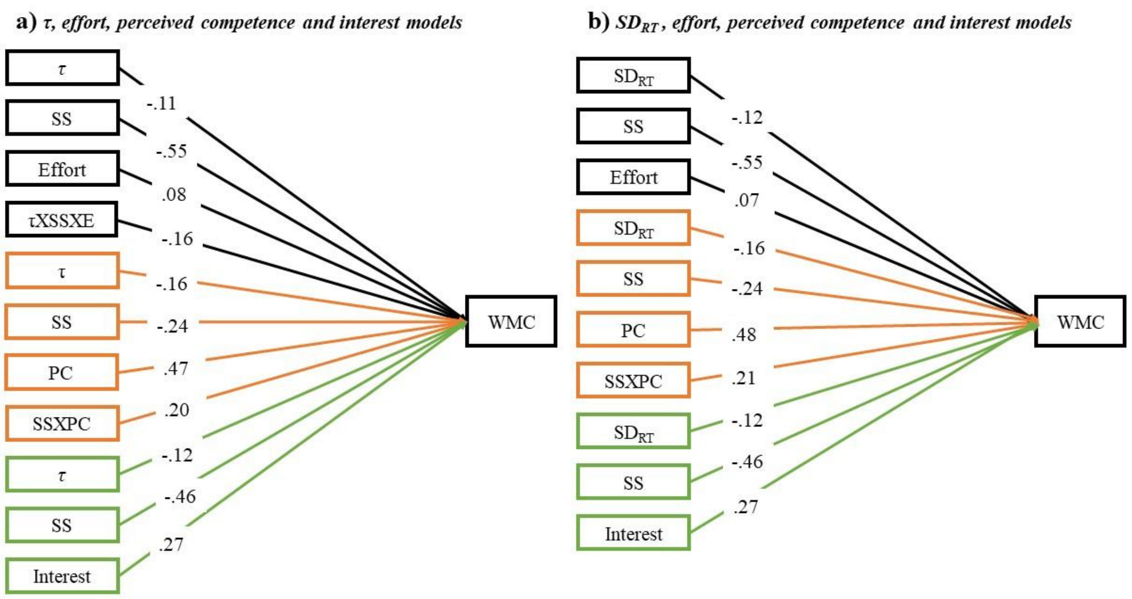
Predictors	*B*	*SE*	*t*	*p*
Constant	.00	.03	.19	.849
SD_{RT}	-.12	.03	-3.70	<.001***
Set Size	-.46	.06	-7.83	<.001***
Half	.05	.06	.78	.435
Interest	.27	.03	9.13	<.001***
NFC	.03	.03	1.04	.297
SD_{RT} x Set Size	.03	.06	.53	.591
SD_{RT} x Half	.05	.06	.80	.418
Set Size x Half	-.12	.11	-1.03	.301
SD_{RT} x Interest	.00	.04	.22	.822
Set Size x Interest	.10	.06	1.79	.072
Half x Interest	-.00	.06	-.08	.940
SD_{RT} x Set Size x Half	.02	.13	.13	.891
SD_{RT} x Set Size x Interest	-.00	.08	-.09	.923
SD_{RT} x Half x Interest	.01	.08	.15	.874
Set Size x Half x PC	.14	.12	1.17	.241
SD_{RT} x Set Size x Half x PC	-.09	.15	-.58	.559

$F(16, 979) = 12.2$, $p < .001$, $R^2 = .17$. SD_{RT} = standard deviation of reaction time. PC = perceived competence; NFC = need for cognition. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

In Summary, Figure 2.5 provides an overview of all significant results of moderation analyses. As seen in Figure 2.5, set size predicted WMC, but not time-on-task. Furthermore, each type of intrinsic motivation predicted WMC; however, we only found a moderation effect between τ, set size and effort but not the interaction between SD_{RT}, set size and effort. Although the interaction of SD_{RT}, set size and effort approached the significance level, it did not reach it.

Figure 2.5

The summary of all significant results of moderation analyses

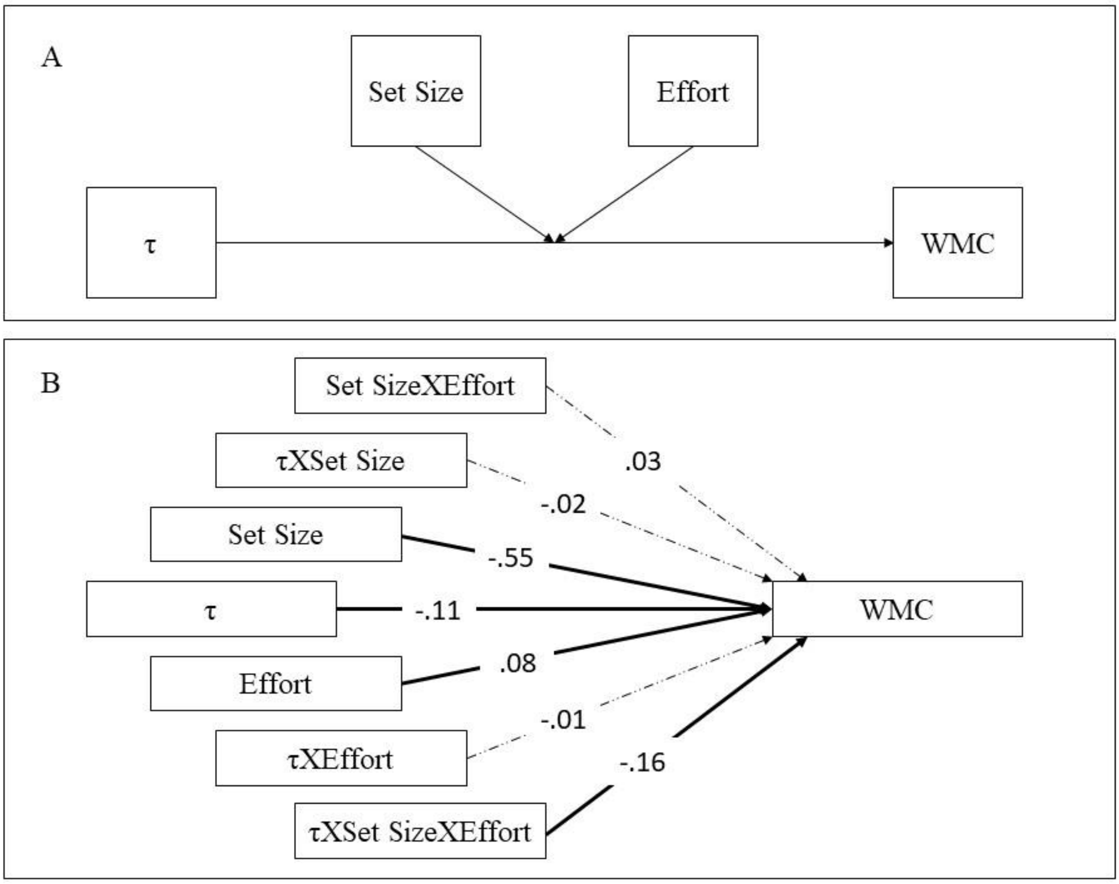


Note. Black colours show effort models. Orange colours show perceived competence models. Green colours show interest models. a represents lapses of attention and b represents attention fluctuations model. τ = tau parameter from Ex-Gaussian; SS = set size; τXSSXE = the interaction between tau, set size and effort; PC = perceived competence; SSXPC = the interaction between set size and perceived competence; SD_{RT} = standard deviation of reaction time.

In addition, Figure 2.6 provides a more detailed depiction of the significant moderation effect of only set size and effort on the relationship between τ and WMC, as outlined in Figure 2.5. Since time-on-task was not a significant predictor, it has been excluded from this figure.

Figure 2.6

Conceptual and statistical illustration of the interaction effect of set size and effort on the relationship between τ and WMC



Note. Panel A presents a conceptual diagram outlining the moderation effect of set size and effort on the relationship between τ and WMC. Panel B provides the statistical representation of this interaction, with solid lines indicating significant paths. The path τXset sizeXeffort is the only moderation effect we found in this study.

2.4 Discussion

The overall aim of this study was to assess two competing theories (resource depletion and mindlessness) by examining under what conditions (task difficulty: low load vs high load; time-on-task: the first half vs the second half) and for whom (individual differences in effort, perceived competence and interest) the relationship between the ability to sustain attention and WMC was stronger. The current study revealed that effort, but not perceived competence or interest, moderated the relationship between lapses of attention, but not attention fluctuations, when task difficulty was low (set size 3).

2.4.1 Theoretical Implications

These findings are consistent with the mindlessness theory but contradict the resource depletion theory. The resources depletion theory suggests cognitive tasks are inherently challenging and demand effort, thereby leading to increased lapses of attention and attention fluctuations as their attentional resources become depleted over time (Warm et al., 2008). Moreover, this theory posits that increased WM load lead to the depletion of the limited resources due to a shared resource, resulting in diminished performance in sustained attention (Caggiano & Parasuraman, 2004; Helton & Russell, 2011, 2013). Hence, the resource depletion account would predict a stronger relationship between WMC differences and individual differences in sustained attention when WM load are high and during the second half of the task. However, the current study showed the opposite.

For the time-on-task effect, in light of the rationale that sustained attention performance during behavioural tasks inevitably decreases with time-on-task (Esterman et al., 2014; Unsworth et al., 2010; Unsworth & Robison, 2020). Moderation models did not reveal any main and interaction effect of time-on-task effect. This suggests that the duration spent on a WM task was not associated with WM performance and time-on-task effect did not influence the strength or weakness of the relationship between WMC and sustained attention.

As with task difficulty, evidence of moderation in the time-on-task effect speaks against resource depletion.

In contrast, the mindlessness theory suggests that decrements in cognitive tasks arise from their monotony and boredom resulting in our attention to shift from the primary task to internal thoughts, task unrelated information or external distractions (Manly, 1999; Robertson et al., 1997). Hence, the mindlessness theory would predict a stronger relationship between WMC and sustained attention in the easy condition rather than the difficult condition. The current study supported this theory. The present study found that individuals with low WMC showed more intra-individual variability in RTs in set size 3 compared to set size 6. In addition, the finding of a correlation between sustained attention and WMC in the low WM load condition was partially in line with the results of a mind-wandering study by Unsworth and Robison (2016). In that study, participants reported being off-task in small set sizes (Unsworth & Robison, 2016). However, our finding was inconsistent with previous mind wandering studies (Baird et al., 2012; Levinson et al., 2012; Rummel & Boywitt, 2014), suggesting a positive relationship between WMC and mind-wandering during undemanding task. Our finding of a negative relationship between WMC and sustained attention in low-demand conditions, particularly when effort levels were lower, indeed suggest support for the mindlessness theory. According to this hypothesis, individuals with lower motivation may be more prone to decreased engagement and/or increased attentional lapses, even in situations where cognitive resources are available. Boring, monotonous, or easy part of the task inherently can lead to disengagement from the task. Indeed, we found that participants reported lower effort levels under low WM load compared to high WM load, even in situations where cognitive resources are not fully depleted. Lower effort levels may contribute to understanding the past findings of increased lapses of attention above and beyond resource depletion theory.

These findings are consistent with several experimental studies (Unsworth et al., 2022; Unsworth & Robison, 2020). For instance, in a study by Unsworth et al. (2022), the experimental group was instructed to try hard (i.e., exert high levels of effort) before a simple RT task and a reduction in lapses of attention was found compared to control group. Furthermore, Unsworth and Robison (2020) found that the association between WMC and lapses of attention partially arises from the voluntary control of attention intensity. The intensity of attention refers to how much attention is devoted to a particular task or stimulus at a particular time. Additionally, Unsworth and Miller (2021) found that intensity is related to intrinsic motivation. Therefore, when individuals exert more effort, individuals with higher WMC sustain higher attention intensity levels. This could potentially reduce the likelihood of experiencing lapses of attention, especially when task difficulty is high. However, it's crucial to note that in our study, motivation was measured in the WM task, not the sustained attention task. Therefore, while we found that WM performance was less related to lapses when effort and set size were higher, we cannot directly infer the level of effort individuals exerted in the RT task. Instead, our findings revealed that the interplay between effort and set size moderated the relationship between WMC differences and variations in sustained attention performance.

These results showed that effort plays a more prominent role in moderating the relationship between WMC and sustained attention compared to perceived competence and interest. This may be due to the association of effort with sustained attention, whereas perceived competence and interest are correlated with both WMC and each other not sustained attention. We found that individuals who exerted more effort on the WM task were more able to sustain attention. Furthermore, the need for cognition was found to have no significant relationship with either sustained attention measures or WMC, indicating that individuals who are inclined to engage in effortful cognitive activities were not necessarily associated with better performance in WM and sustained attention tasks. However, need for cognition was included in all models to account for trait motivation.

Limitations and Future Directions

One limitation of the present study is that the ability to maintain sustained attention was not assessed by continuous performance task (CPT) and sustained attention to response task (SART), which require detecting infrequent trials. Given that these types of sustained attention task require greater attentional control, it may exhibit a stronger correlation with WMC under challenging task conditions. This would have contributed to a better understanding of the relationship between WM, attentional control and sustained attention as distinct constructs, particularly when using sustained attention tasks such as the psychomotor vigilance task and simple RT task that do not involve attentional control demands. The remainder of the thesis examines whether sustained attention and attentional control are distinct and whether sustained attention mediates the association between WM and fluid intelligence above and beyond attentional control.

Second limitation of the present study is that current mood levels (boredom, anxiety, stress levels or current concerns) and alertness, characterized by heightened awareness and readiness to respond to stimuli or tasks (Unsworth & Robison, 2020), were not examined in the current study. Previous studies suggested that participants tend to experience more lapses of attention when they are stressed, bored, anxious, or preoccupied with current concerns (Malkovsky et al., 2012; McVay & Kane, 2010; Sliwinski et al., 2006; Unsworth, Robison, et al., 2021b). Current mood levels may play a moderator role the relationship between WMC and sustained attention. More importantly, Unsworth and Robison (2020) found that the relationship between WMC and sustained attention arises partially from alertness, suggesting the importance of alertness component of sustained attention. Hence, future research will need to investigate the moderation effect of current mood levels on the relationship between WMC and sustained attention. In addition, future research is needed to examine how alertness and attention control component of sustained attention related to WMC differences.

2.5 Conclusion

To conclude, this study provides evidence supporting the mindlessness theory by showing that the association between sustained attention – in particular lapses of attention – and WMC is strongest when WM demands are low and low effort is exerted. The findings contradict resource depletion theories, given that the correlation between WMC and sustained attention did not strengthen under high WM load or during the second half of the task. Given the moderator role of effort on the relationship between WMC and lapses of attention – in particular in contrast to task-specific factors (set size and time-on-task) – intrinsic motivation may explain this relationship after resource depletion. Future research will need to investigate how WMC differences will relate to different aspects (alertness and attention control) of sustained attention to better understand the relationship between WMC and sustained attention.

CHAPTER 3 – Does Sustained Attention Explain the Relation Between Working Memory and Fluid Intelligence?

Contributions:

Hakan Atis (conceptualization, data collection, data analysis, methodology, writing, and visualization)

Daniel J. Carroll (supervision)

Claudia C. von Bastian (supervision, administration, conceptualization, finding acquisition, methodology, review, and editing)

Conference presentation from this Chapter

This Chapter has been accepted for poster presentation at the 4th International Conference on Working Memory (ICWM), scheduled to take place between 25-27 June 2024.

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Abstract

Working memory (WM) is highly correlated with fluid intelligence (Gf), but it is yet unclear why. Previous research has suggested that common attentional processes explain this relation without, however, distinguishing between attentional control and sustained attention. Therefore, the present study investigated whether sustained attention – attention fluctuation and lapses of attention – mediates the relationship between WM and Gf above and beyond attention control. *N* = 144 participants completed a battery of 12 tasks, with 3 tasks each assessing WM, Gf, attention control and sustained attention. Contrary to our expectations, the findings suggest that neither attention control nor sustained attention mediated this relationship. These findings challenge the prevailing theory that attention control is the primary driver of the WM-Gf association, highlighting the need for further research to better understand the underlying mechanisms at play.

3.1 Introduction

Numerous studies on WM have explicitly demonstrated that WM has significant predictive power for individual differences in Gf (Chuderski, 2013; Conway et al., 2002; Kane et al., 2005; Kyllonen & Christal, 1990; Oberauer et al., 2005; Unsworth et al., 2014). Gf refers to the ability of learning new information and solving novel problems (Cattell, 1963). These studies indicate that individuals with high WMC perform better in fluid intelligence tasks than those with low WMC. Many WM models assume that the domain-general executive attention component of WM, sometimes referred to as a central executive or attentional control (see Logie et al., 2020) underpins the predictive power of WMC on complex cognition. Thus, attentional processes may emerge as pivotal drivers in understanding this relationship WMC-Gf.

Attentional processes distinguish between two forms of information processing: controlled and automatic processing. The theoretical framework is called the dual processing framework. While some actions do not require conscious and effortful processing, known as automatic processing, others need conscious awareness, effort, or controlled processing. In automatic processing, attention helps to select and prioritize relevant stimuli for processing, even when individuals are not consciously aware of it. In controlled processing, attention is intentionally directed toward specific tasks or goals, allowing individuals to focus on complex problem-solving, decision-making, or planning. On the one hand, for example, as the teacher speaks, the student's mind begins to wander, and they find themselves daydreaming about weekend plans or upcoming events. Despite their best intentions to focus on the lecture, these lapses of attention occur spontaneously, in the presence of automatically generated thoughts and without deliberate control. Indeed, some researchers suggested that failures in sustained attention, such as momentary distractions, mind wandering, or zoning out, sometimes occur spontaneously and without intentional control (Mason et al., 2007;

McVay & Kane, 2010; Seli et al., 2015). On the other hand, while individuals may sometimes employ controlled processing to prevent lapses of attention, conscious efforts to maintain attention may help reduce the frequency or duration of lapses, but the initial occurrence is often involuntary. For example, individuals may make a conscious effort to stay focused by actively engaging in the discussion, taking notes, and periodically asking clarifying questions. However, as the meeting progresses, they may find their drifting off momentarily, thinking about unrelated personal goals. Recognizing this lapse of attention, they quickly control their thoughts back to the meeting agenda and actively participate in the discussion. Thus, while sustained attention may be more about aspects of automatic processing, attention control is more about aspects of controlled processing.

Evidence from cognitive neuroscience indicating that sustained attention and attention control are localised in distinct brain networks supports the dual processing framework. Cortical activation in the frontal and parietal hemispheres is associated with sustained attention performance, while attention control performance in the conflict task such as the Stroop test is associated with the anterior cingulate and the lateral prefrontal cortex (for a review, see Petersen & Posner, 2012; Posner & Petersen, 1990). The vigilance system, also referred to as sustained attention over time. The vigilance system relates to automatic stimulus selection, enabling an individual to be prepared for incoming stimuli. For instance, when anticipating an important email, the vigilance network maintains a state of readiness to notice its arrival. In contrast, the attention control system is closely associated with controlled processing, actively resisting interference, and resolving conflict among responses. The attention control system is crucial for higher-level cognitive tasks that require deliberate and goal-directed attention. Fan and colleagues (2002) designed the Attention Network Test (ANT) to investigate whether individual differences in vigilance, measured continuous and vigilance task, and individual differences attention control networks, measured the flanker task, were associated with each other. They found no correlation between individual differences in performance in these tasks. These findings suggest that sustained attention and attention control reflect distinct facets of attentional processes.

A recent latent variable study by Unsworth, Miller and Robison (2021) provided evidence for sustained attention and attention control being distinct constructs. They investigated whether sustained attention and attention control loaded on the same construct. The authors reported that individual differences in sustained attention and attention control are strongly related (r = - 0.65) but distinct factors. It is worth noting that although sustained attention was found to be a different construct and related to WMC and attention control, the relationship between WMC, sustained attention, and Gf was not examined in that study. This distinction aligns with the overarching framework proposed by von Bastian et al. (2020), where attentional control serves as the broader category encompassing sustained attention and attention control as distinct but related. Despite the evidence for these two being distinct constructs, sustained attention and attention control are often implicitly subsumed under the umbrella term of attention control, as reflected by using tasks measuring sustained attention (e.g., SART, CPT, PVT) to assess attention control (Robison & Brewer, 2022; Unsworth et al., 2009, 2014).

Especially, the attention control theory of WMC (Engle, 2002; Engle & Kane, 2004), which is one of the predominant theories explaining the robust relationship between WM and Gf and aligning with the concept of controlled processing, assumes that sustained attention is a fundamental component of attention control. According to this theory, WMC "is not really about storage or memory per se, but about the capacity for *controlled*, *sustained attention* in the face of interference or distraction" (Engle et al., 1999a, p.103). This definition suggests that individual differences in WMC use the ability to sustain attention for maintenance information in WM in the face of interference or distraction, thereby reflect a domain-general attention control as a controlled processing.

Direct evidence for the attention control theory came from some quasi-experimental approaches (Heitz & Engle, 2007; Kane et al., 2001; Kane & Engle, 2003; Unsworth et al., 2004). In these studies, participants were divided into high and low span groups based on their performance in a complex span task. Subsequently, these studies investigated whether individuals with high and low spans differed in their performance on attention control tasks. The results consistently showed that participants with high spans demonstrated greater accuracy and quicker responses compared to those with low spans in the anti-saccade task, flanker task and Stroop task. These findings suggested that WMC differences become crucial when attention control processes were involved, particularly in tasks requiring attention control but not requiring recall beyond its own task goals and not involving sustained attention.

More recently, the maintenance and disengagement theory, an extension of the attention control theory, has attempted to explain the relationship between WMC, Gf and individual differences in attentional control. The maintenance and disengagement theory suggests that both WM and Gf require the ability to effectively control one's attention. This theory proposes that WM-Gf abilities are realised through a single top-down attention control system, comprising two broad attentional control mechanisms: maintenance and disengagement. This system primarily operates through the maintenance of goal-relevant information in memory and the disengagement from outdated or irrelevant information, both of which contribute to WM and Gf to varying degrees (Burgoyne & Engle, 2020; Engle, 2018; Mashburn et al., 2020; Shipstead et al., 2016). This theory is based on the idea that WM and fluid intelligence constructs entail distinctly different cognitive demands. WM require individuals to manage both storing and processing information, while Gf do not necessitate explicit memory storage but instead involve deducing connections in new problems to find solutions. WM tasks are place demands mostly on the mechanism of maintenance, as participants in complex span tasks need to actively retain memory representations for ongoing cognition. In contrast, Gf tasks reflect primarily to the ability to disengage from no-longer relevant information for ongoing cognition or for when maintaining information becomes outdated. Tasks assessing WMC and Gf still involve maintenance or disengagement mechanisms to at least some extent. Therefore, the ability to control attention is common factor between two other abilities.

However, two controversial issues arise. One of them is that there is conflicting evidence as to whether attentional control really explains the relationship between WM and Gf. Second, there is debate about how sustained attention is conceptualised and its relationship with WMC and Gf. A study by Rey-Mermet and colleagues (2019) reported that attentional control is not significantly correlated with WM and Gf, contradicting the predictions of the maintenance and disengagement theory. Similarly, Chuderski et al. (2012) found that attention control was not significantly related to Gf. Furthermore, some studies reported that attention control did not fully mediate the relationship between WMC and Gf (Burgoyne et al., 2023; Unsworth et al., 2009, 2014). These studies have prompted suggestions that factors beyond attentional control may serve as mediators in this relationship.

The second controversial issue how sustained attention is conceptualised. According to the maintenance and disengagement theory, sustained attention is considered a fundamental aspect of attentional control, with a strong overlap between sustained attention and the ability to maintain information in working memory despite distractions (Tsukahara & Engle, 2023). From this theory, the tasks postulated to measure the ability to sustain attention such as the psychomotor vigilance task (PVT), the continuous performance task (CPT) the sustained attention to response task (SART) and the sustained attention to cue task are frequently examined under the attention control factor (Tsukahara & Engle, 2023; Unsworth et al., 2009). SART, CPT and sustained attention to cue task require to distinguish targets from non-targets. Therefore, previous research forms attention control with a factor comprising a sustain attention task and these studies did not assess specifically performance change in RTs over time as a different coherent sustained attention factor (Burgoyne et al., 2023; Robison & Brewer, 2022; Unsworth et al., 2009, 2014).

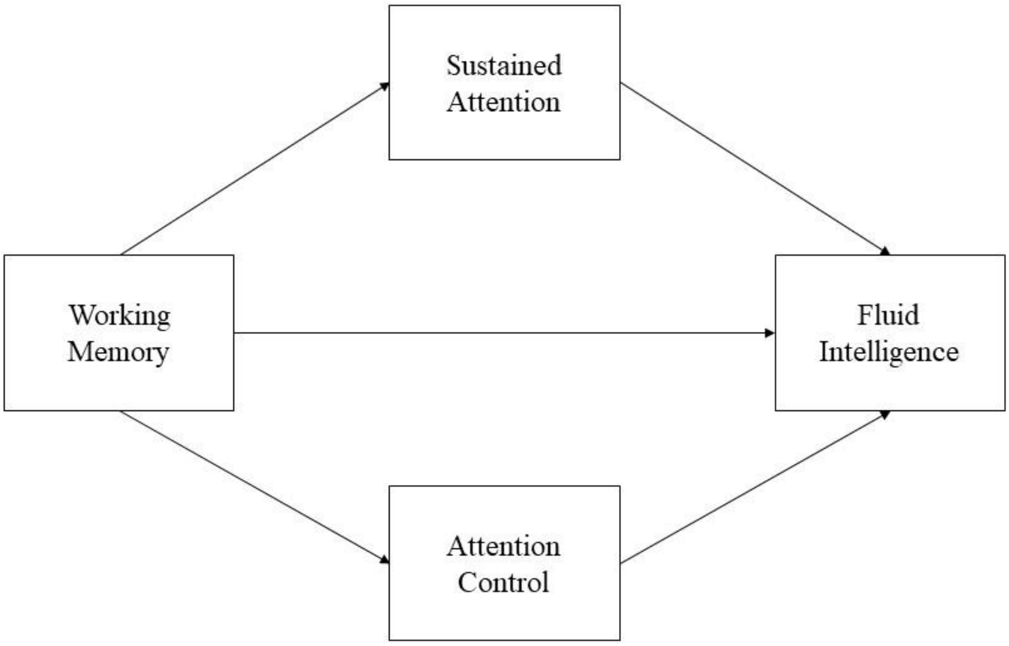
Therefore, sustained attention as a more basic or automatic process may be also conceptualized as readiness respond to a stimulus over time. For example, some individuals tend to perform more longer RTs (lapses of attention) and more changes intraindividual RTs (attention fluctuations) across time, thereby may predict lower WMC and lower Gf. Sustained attention was found to be associated with WMC and Gf in a study using the PVT task that involved only responding to stimuli appeared on the screen (Unsworth et al., 2010). In contrast this finding, some studies found that sustained attention did not significantly correlated to WMC and Gf (Robison & Brewer, 2022; Tsukahara & Engle, 2023). Therefore, it is still unclear the specific contribution of sustained attention as a distinct construct from attention control to the relationship between WMC and Gf.

3.1.1 The Present Study

To address the gap regarding how sustained attention as a more basic process and distinct from attention control contribute to the relationship between WM and Gf, the goal the present study was to investigate whether sustained attention is distinct construct from attention control and whether sustained mediates the relationship between WM and Gf. Considering the studies that state that sustained attention is separate from attention control (Tsukahara & Engle, 2023; Unsworth, Robison, et al., 2021b), we expect that sustained attention is a factor different from attention control. Furthermore, we expect that sustained attention affects the relationship between WM and Gf after accounting for attentional control (see Figure 3.1 for hypothesised mediation model). To address this, we examined this question at the latent variable level, so we administered 12 tasks, three tasks for each construct.

Figure 3.1

Hypothesised mediation model



Note. Sustained attention and attention control were hypothesised to mediate the relationship between working memory and fluid intelligence.

3.2 Materials and Methods

3.2.1 Participants

The sample included in this study were 144 participants (74 men M_{age} = 48.67, SD_{age} = 18.37; 70 women; M_{age} = 48.45, SD_{age} = 18.50; age range 18-85 years) who were part of a larger study (von Bastian et al., 2022). Participants were recruited for a multi-site cognitive training study through institutional participant pools, Facebook ads and other social media, and posters and leaflets that were distributed in local communities. Only participants recruited from the University of Sheffield for the United Kingdom site were included in the present study because data from other study sites, including the Medical School Hamburg in Germany and the Centre de Recherche de l'Institut Universitaire de Gériatrie de Montréal, was not available at the time this thesis was written.

Participants reported whether they met inclusion criteria during a phone screening. Inclusion criteria were age between 18 and 85 years, fluency in English, good health, and no current diagnosis of neurological, psychological, or psychiatric illness. In addition, colour blindness and daily use of drugs (e.g., cannabis) and/or excessive alcohol (more than about 25 units per week in the UK) use were exclusion criteria. Furthermore, before the laboratory assessment started, the pen-and-paper version of the Montreal Cognitive Assessment (the MoCA, version 8.1; Nasreddine et al., 2005) was administered. Participants 55 years or older who scored less than 24 points in the MoCA were excluded from the study (N = 3 at the UK site). Participants received either course credit or Amazon e-vouchers for their participation (£125). The University of Sheffield Research Ethics Committee approved this study.

3.2.2 Procedure and Materials

The original study from which the data was used in the study of von Bastian and colleagues (2022). Therefore, the procedure used in the study by von Bastian and colleagues in this part will be described below. Data collection was employed at three different places: The University of Sheffield in the United Kingdom, the Medical School Hamburg in Germany, and the Centre de Recherche de l'Institut Universitaire de Gériatrie de Montréal. The same study protocol involving the study coordinator, experimenter handbook with well-matched versions in all languages, and phone screening, was followed in all sites. Participants were tested individually. The data in the present study includes data from three working memory tasks (updating, binding, and continuous reproduction), three simple reaction time (RT) tasks (drawings, shapes, and numbers), three attentional control tasks (go/no-go, Stroop, and Simon), and three fluid intelligence tasks (raven, paper folding, and letter sets). An experimenter was present outside of the room for any questions and support during the test session. The tasks were administered via Tatool Web, a free, open-source tool for behavioural experiments (www.tatool-web.com: von Bastian et al., 2013).

3.2.3.1 Working Memory Tasks

Continuous Reproduction (Fougnie & Alvarez, 2011). Participants were asked to memorise the orientations of five triangles. These triangles were presented for 1200 ms and appeared on the screen simultaneously. At the beginning of each trial, a fixation point was presented for 500 ms, followed by a 900 ms retention interval. Next, one triangle was presented at a random location and in a random orientation. The participant's task was to reproduce the original orientation using the mouse. The task consisted of 100 test trials. The dependent variable was the signed response error in degrees.

Binding (Guye & von Bastian, 2017; Oberauer, 2005). Participants were asked to memorise a set of sequentially presented associations between coloured triangles and their location in a 4 x 4 grid. After that, participants were asked to recognize whether these triangles were demonstrated at the respective locations. Three to 5 triangles appeared sequentially on the screen for 900 ms, and a blank interval for 100 ms followed this phase. After participants memorised, each association was probed using the position as cue. Participants were asked to determine whether the association matched one of those presented during the memorization phase. Half of the probes were matched, and the other half were intrusions. Probe locations for intrusions were distributed randomly. Each trial was followed by a 100 ms blank interval. Participants completed 24 test trials. The dependent variable was the discrimination parameter *d*’, which is the difference between z-transformed hit rates to match probes and z-transformed false alarm rates to intrusion probes.

Updating (Miyake et al., 2000; von Bastian et al., 2016). In this task, three single numbers within three side-by-side boxes simultaneously appeared on the screen for 3750 ms at the onset of the task. A blank interval of 250 ms followed this phase. Participants were initially asked to memorise the three digits. After that, these numbers were replaced by new digits, and each new digit was presented for 1250 ms, followed by a blank interval for 250 ms. Participants’ task was to memorise the most recent number that shows in each of the three boxes, and they reported sequentially the most recent number for the respective box. These three boxes were equally substituted across all 18 trials, meaning that each of the three boxes was replaced six times. The dependent variable was the proportion of correctly remembered digits.

3.2.3.2 Simple Reaction Time (RT) Tasks

Three simple RT tasks similar to the task in Study 1 were employed to measure the ability to sustain focused attention. The simple RT tasks were administered in three types of stimuli (drawing, shapes, and numbers). Participants were asked to press the space button on a computer keyboard as soon as possible when the stimulus appeared on the screen. Task duration throughout was 5 minutes. The interval between the presentation of the two stimuli was randomly adjusted, ranging from 150 ms to 1170 ms, and the participants saw a white screen during this time. The stimuli in the three types of simple RT tasks were presented randomly and with equal frequency. The dependent variable was the τ estimates from Ex-Gaussian distribution and SD_{RT}. These τ estimates are indicative of lapses of attention, which are characterized by temporary breaks in sustained attention. By focusing on the tail of the RT distribution, τ estimates provide a specific measure of the occurrence and duration of attentional lapses during a task (Unsworth et al., 2010). The standard deviation of reaction time (SD_{RT}) reflects the variability in RTs across trials. High SD_{RT} values indicate greater variability in attentional engagement, suggesting fluctuations in the ability to maintain consistent performance over time. Attention fluctuations encompass not only lapses of attention but also periods of heightened attentional focus and variability in attentional engagement throughout the task (Esterman et al., 2014; Esterman & Rothlein, 2019).

3.2.3.3 Fluid Intelligence Tasks

Raven's Advanced Progressive Matrices (short form; Arthur & Day, 1994; Arthur et al., 1999). Participants were asked to select the missing piece that completes a pattern. Participants needed to choose 1 of 8 options. The time limit for this task was 15 minutes, and the task consisted of 12 trials. The dependent variable was the proportion of correct responses out of 12.

Paper folding: A folded piece of paper was presented. Participants were asked to identify how the paper looked when unfolded. Participants needed to select 1 of 5 options. The task consisted of two blocks, and each block had 10 trials. The time limit was 3 minutes for each task. The dependent variable was the proportion of correct responses out of 20 (Ekstrom et al., 1976).

Letter Sets Part II: Five sets of four letters were presented in each trial. Four of these sets were presented in a logical sequence of letters. Participants were asked to identify the different letter sets which did not follow a logical pattern. The task had 15 trials and the time limit was 7 minutes. The dependent variable was the proportion of correct responses out of 15 (Ekstrom et al., 1976).

3.2.3.4 Attention Control Tasks

Go/No-Go (Chuderski et al., 2012). Participants performed a Go/No-Go task where they were presented with visual stimuli on a computer screen. They were instructed to respond by pressing the spacebar when presented with a square (Go trials), and to withhold their response when presented with a diamond (No-go trials). A total of 288 trials were administered, with 75% being Go trials and 25% being No-go trials. The dependent variable measured was the discrimination parameter *d*’, which is the difference between z-transformed hit rates (proportion of correct responses to Go trials) and z-transformed false alarm rates (proportion of incorrect responses to No-go trials).

Number Stroop (Salthouse & Meinz, 1995; von Bastian & Oberauer, 2013). Participants completed a number Stroop task, where they were presented with sequences of digits on a computer screen. Participants were required to indicate the number of digits presented on the screen while suppressing their predominant response to instead indicate to the value of the digits shown. A total of 288 trials were administered, consisting of 75% congruent trials (e.g., "2222") where the number of digits matched the value represented, and 25% incongruent trials (e.g., "44") where the number of digits conflicted with the value represented. The dependent variable was the discrimination parameter *d′* for RT, which is the difference between z-transformed hit rates (mean RT for congruent trials) and z-transformed false alarm rates (mean RT for incongruent trials). Higher *d*’ values indicate better inhibition of incongruent stimuli and stronger focus on task-relevant information, whereas lower values suggest less effective inhibition and potential distraction from incongruent stimuli.

Simon (Simon, 1969; von Bastian et al., 2016). Participants were instructed to press the "A" key for green circles and the "L" key for red circles, which were the presented on the left or right of the screen. A total of 288 trials were administered, comprising 75% congruent trials where the colour and location of the circle matched (e.g., a red circle presented on the right side) and 25% incongruent trials where the colour and location of the circle conflicted (e.g., a red circle presented on the left side). The dependent variable was the discrimination parameter *d*’ for RT, which is the difference between z-transformed mean RT for congruent trials and z-transformed mean RT for incongruent trials. Higher *d*' values indicate greater sensitivity to detecting differences between congruent and incongruent trials, whereas lower values suggest reduced sensitivity.

3.3 Results

All analyses were conducted in R (version 4.2.2; R Core Team, 2022). Confirmatory factor analyses and mediation models with composite scores were run with the lavaan package (Rosseel, 2012).

3.3.1 RT Cleaning Procedures and Data Exclusions

For sustained attention tasks, only correct responses were included in the analysis, and trials with RTs less than 100 ms were removed. Regarding attentional control tasks, specifically Stroop and Simon, only RTs for correct responses were considered. Additionally, RTs were subjected to trimming, excluding any values more than 3 median absolute deviations away from the overall median (Leys et al., 2013). This trimming was conducted individually for each participant and condition (e.g., congruent and incongruent).

One participant was excluded from the dataset on the suspicion of confusing congruent and incongruent trials because the participant responded to the incongruent trials as if they were congruent, indicating confusion between the two trial types. In addition, the final dataset was checked for multivariate outliers using Mahalanobis distance (Leys et al., 2018), resulting in 11 multivariate outliers in the dataset (~8% of participants). Data from these participants were removed.

3.3.2 Descriptive Statistics and Correlations

Descriptive statistics for measures of sustained attention, WM, attention control and fluid intelligence are shown in Table 3.1. Given its high accuracy rate of 95%, the updating task was excluded from further analyses in this study due to the presence of a ceiling effect.

Table 3.1

Descriptive statistics for all measures

Measure	*M*	*SD*	*Min*	*Max*	Skew	Kurtosis
Numbers (τ)	68.05	35.98	22.83	186.66	1.37	1.40
Drawings (τ)	61.83	29.91	20.46	219.46	2.03	6.52
Shapes (τ)	63.51	28.77	1.32	166.34	1.15	1.56
Numbers (SD_{RT})	102.30	61.37	31.77	373.60	1.88	4.15
Drawings (SD_{RT})	81.15	55.83	25.69	513.24	4.70	29.21
Shapes (SD_{RT})	90.61	43.72	40.20	296.66	1.87	4.66
Binding (*d*')	1.62	0.83	-0.20	3.76	-0.10	-0.30
Updating (proportion correct)	0.95	0.10	0.5	1	-3.20	9.81
Recall Errors (degrees)	-58.17	15.10	-93.26	-23.66	0.09	-0.63
Stroop Congruency (*d*')	-0.17	0.07	-0.35	-0.01	-0.12	-0.23
Simon Congruency (*d*')	-0.17	0.07	-0.41	-0.02	-0.62	0.47
Go/No-Go (*d*')	4.17	0.55	2.70	5.29	0.04	-0.17
Raven (proportion correct)	0.50	0.23	0	1	0.11	-0.76
Paper Folding (proportion correct)	0.69	0.22	0.1	1	-0.61	-0.58
Letter Sets (proportion correct)	0.68	0.17	0.6	1	-0.77	0.76

Note. τ = tau parameter obtained from Ex-Gaussian; SD_{RT} = standard deviation of reaction time; *d'* = detection performance; degrees = the signed response error in degrees.

Correlations are shown in Table 3.2. The correlations between the tasks ostensibly assessing the same constructs were weak to moderate in magnitude.

Table 3.2

Correlations of variables for confirmatory factor analysis

Measures	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Raven														
2. Letter Sets	**.37*** **													
3. Paper Folding	**.59*** **	**.33*** **												
4. Go/No-go	-.06	**.26** **	-.02											
5. Stroop	-.09	.03	**-.22** **	**.30** **										
6. Simon	.03	.13	.04	**.24** **	**.24** **									
7. Updating	**.40*** **	**.49*** **	**.47*** **	.12	-.02	**.17* **								
8. Binding	**.40*** **	**.41*** **	**.35*** **	-.05	-.11	.16.	**.44*** **							
9. Continuous Reproduction	**.54*** **	**.18* **	**.40*** **	.02	-.16.	.04	**.33*** **	**.64*** **						
10. Numbers SD_{RT}	-.06	.05	-.08	.13	**.18* **	**.25** **	-.01	.16.	.02					
11. Drawings SD_{RT}	.11	.02	-.00	-.07	.07	.16.	.03	**.24** **	.11	**.59*** **				
12. Shapes SD_{RT}	.14	.10	-.03	.12	**.22** **	**.21* **	.05	**.25** **	**.25** **	**.51*** **	**.34*** **			
13. Numbers τ	-.03	.04	-.05	.04	.14	**.24** **	.02	**.24** **	.07	**.91*** **	**.55*** **	**.58*** **		
14. Drawings τ	**.17* **	.01	.02	-.11	-.00	.15.	.08	**.32*** **	**.21* **	**.54*** **	**.87*** **	**.48*** **	**.58*** **	
15. Shapes τ	.14	.05	-.00	-.00	**.17* **	**.19* **	.09	**.29*** **	**.21* **	**.52*** **	**.40*** **	**.92*** **	**.68*** **	**.57*** **

Note. Bold correlations are significant. SD_{RT}= standard deviation of reaction time; τ = tau parameter from Ex-Gaussian. ***p <.001, **p <.01, *p <.05.

3.3.3 Confirmatory Factor Analyses

First, we examined whether the indicators of attention control and sustained attention assess the same construct or separate but related factors. Second, we examined the relation between WM, Gf, attentional control and sustained attention constructs, and whether attentional control and sustained attention mediated the relation between WM and Gf. Age was included in all of these models as covariates. All analyses were conducted once for lapses of attention, and once for attention fluctuations. after all variables had been *z*-standardized. Furthermore, all scores were coded so that greater positive values indicate better performance.

All model testing used several fit statistics. Non-significant chi-square goodness of fit tests ($\chi 2$), standardized root mean square residual (SRMR) and root mean square error of approximation (RMSEA) of ≤ .08, and a Comparative Fit Index (CFI) of ≥ .90 were considered acceptable fit (Hu & Bentler, 1999; Schermelleh-Engel et al., 2003). Lavaan's bootstrap estimation approach (10,000 samples) was used to obtain 95% bias corrected confidence intervals (95% CI).

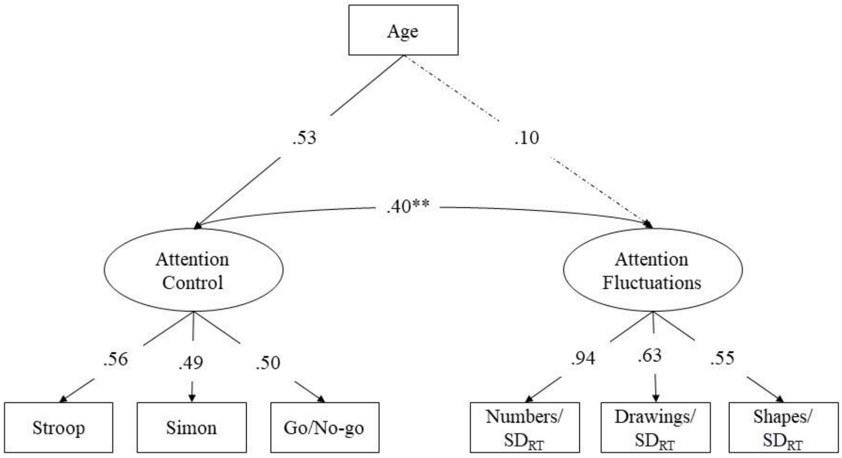
Measurement Models of Attentional Control and Attention Fluctuations

The first confirmatory factor analysis examined whether attentional control and attention fluctuations, as an aspect of sustained attention, were best considered as a common attentional control factor, or as separate but related factors. In order to test the question, we specified a one-factor model, where attentional control and attention fluctuations indicators loaded onto a single common factor, and a two-factor model, where attentional control and attention fluctuations indicators loading onto their respective factors. The one-factor model yielded a poor fit, $\chi 2(9) = 30.710$, $p < .001$, SRMR = .09, RMSEA = .13, 90% confidence interval (CI) [.08 - .18], CFI = .83. The standardized factor loadings were all significant except for the Go/No-go task (Stroop = .22, $p = .020$; Simon = .30, $p = .002$, Go/No-go = .15, *p* = .116; Numbers Simple SD_{RT} = .91, $p < .001$; Drawings Simple SD_{RT} = .64, $p < .001$; Shapes Simple SD_{RT} = .57, $p < .001$).

Next, attention fluctuations measures were loaded on a separate but correlated factor (see Figure 3.2). The overall fit of the two-factor model was good, $\chi 2(8) = 12.33$, $p < .137$, SRMR = .06, RMSEA = .06, 90% CI [.00 - .13], CFI = .97. The standardized factor loadings were all significant (Stroop = .56, $p < .001$; Simon = .49, $p < .001$, Go/No-go = .50, $p < .001$; Numbers Simple SD_{RT} = .94, $p < .001$; Drawings Simple SD_{RT} = .63, $p < .001$; Shapes Simple SD_{RT} = .55, $p < .001$). Importantly, the two-factor model fitted significantly better than the one-factor model, $\Delta\chi 2(1) = 18.38$, $p < .001$, suggesting that a two-factor model with separate attentional control and attention fluctuations factors best accounted for the data. The two factors correlated moderately (.40), indicating that people with higher attentional control abilities possess more attention consistency. This result suggests that attention control and sustained attention are distinct but related constructs.

Figure 3.2

A two-factor model with attention fluctuations and attention control



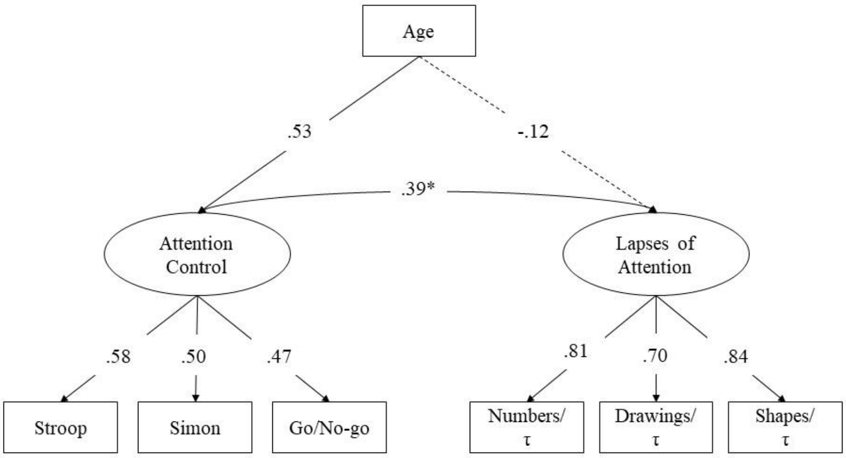
Note. Figure 3.2 shows the measurement models of attentional control and attention fluctuations. Solid line indicates significant and dashed line indicates non-significant. SD_{RT}= standard deviation of reaction time. ****p* <.001, ***p* <.01, **p* <.05.

Measurement Models of Attentional Control and Lapses of Attention

Next, we conducted the same analyses for lapses of attention. Like for attention fluctuations, the one-factor model showed inadequate fit, $\chi 2(9) = 33.138$, $p < .001$, SRMR = .10, RMSEA = .14, 90% CI [.09 - .19], CFI = .86. The standardized factor loadings were all significant except for Stroop and Go/No-go (Stroop = .16, *p* = .081; Simon = .26, *p* = 006, Go/No-go = .01, *p* = .952; Numbers Simple τ = .83, *p* < .001; Drawings Simple τ = .69, *p* < .001; Shapes Simple τ = .83, *p* < .001. In contrast, the overall fit of the two-factor model was acceptable, $\chi 2(8) = 13.984$, $p < .082$, SRMR = .07, RMSEA = .07, 90% CI [.00 - .13], CFI = .97, and significantly better than the one-factor model, $\Delta\chi 2(1) = 19.15$, $p < .001$. Figure 3.3. illustrates the two-factor model. The standardized factor loadings were all significant (Stroop = .58, *p* < .001; Simon = .50, *p* < 001, Go/No-go = .47, *p* < .001; Numbers Simple τ = .81, *p* < .001; Drawings Simple τ = .70, *p* < .001; Shapes Simple τ = .84, *p* < .001). Similar to attention fluctuations, lapses of attention were significantly correlated with attention control, $r = .39$, $p = .013$.

Figure 3.3

A two-factor model with lapses of attention and attention control



Note. Figure 3.3 demonstrates the measurement models of attentional control and lapses of attention. Solid line indicates significant and dashed line indicates non-significant. τ = tau parameter from Ex-Gaussian Distribution. ****p* <.001, ***p* <.01, **p* <.05.

Attention Fluctuations and Lapses of Attention Models After Controlling for Age

Next, we specified a model with separate factors for WM (based on discrimination parameter in the Binding task and recall errors in Continuous Reproduction task), attention fluctuations, attention control, fluid intelligence (based on proportion correct in the Raven Letter Sets, Paper Folding) and age as a covariate. It was allowed for all variables to load only on their respective factors and correlations were allowed among all factors, including age. The model fit was poor, $\chi2(46) = 120.012$, $p < .001$, SRMR = .09, RMSEA = .11, 90%

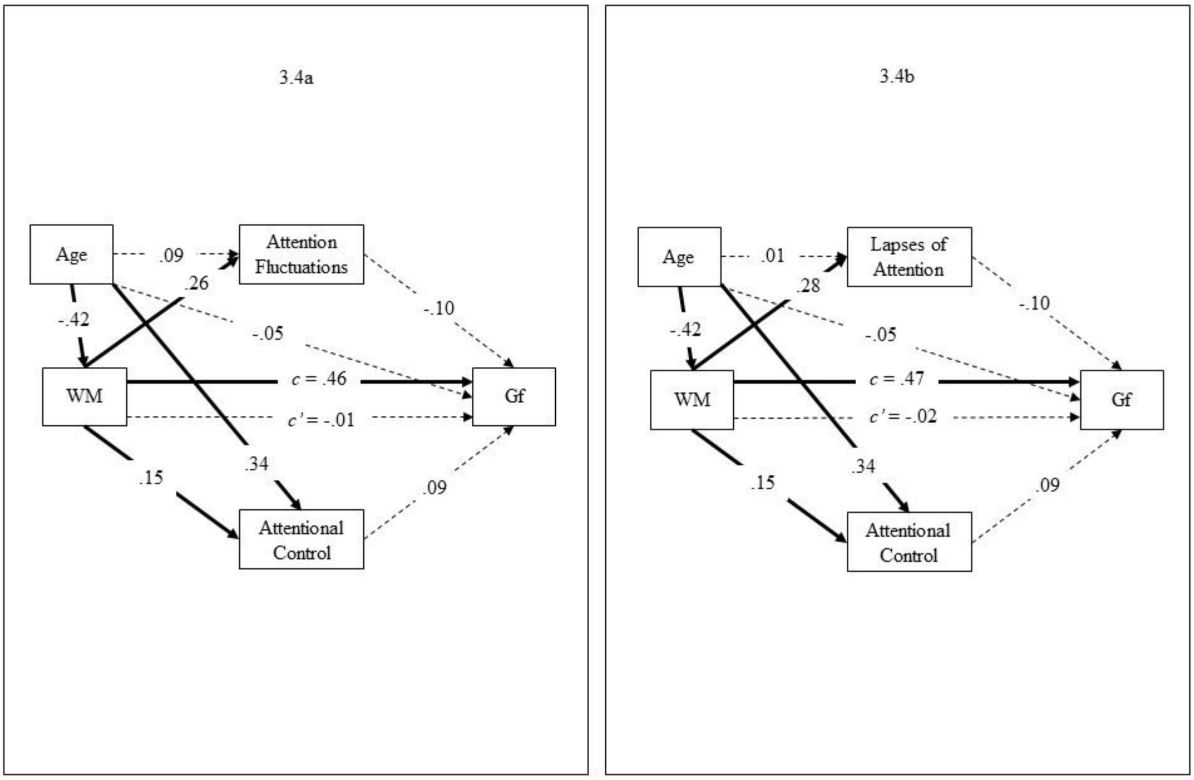
CI [.08 - .13], CFI = .84. Similarly, the overall fit of the model including WM, Gf, lapses of attention, attentional control and age as a covariate was poor, $\chi2(46) = 120.813$, $p < .000$, SRMR = .08, RMSEA = .11, 90% CI [.08 - .13], CFI = .85. Therefore, to conduct mediation analyses, we decided to proceed with manifest variables based on composite scores of performances in the tasks loading on the relevant factors.

3.3.4 Mediation Analysis with Composite Scores

We examined two separate mediation models for both aspects of sustained attention illustrated in Figure 3.4, to examine whether sustained attention – operationalised as attention fluctuations (Figure 3.4a) and lapses of attention (Figure 3.4b) mediates the relation between WM and Gf above and beyond attentional control. In both models, we accounted for age as a continuous covariate.

Figure 3.4

An overview of the mediation results with composite scores



Note. 3.4a shows the mediation results with composite score for attention fluctuations. 3.4b demonstrates the mediation results with composite score for lapses of attention. Solid line indicates significant and dashed line indicates non-significant. c shows direct effect and c' demonstrates indirect effect. WM = working memory; Gf = fluid intelligence.

Mediation Model of Attention Fluctuations

We found that WM was related to attention fluctuations and attentional control, indicating that individuals with better WM showed less attention fluctuations, $b = 0.26$, 95% CI [.09 - .43], $z = 3.20$, $p = .002$, and attentional control performance, $b = 0.15$, 95% CI [.10 - .46], $z = 2.06$, $p = .040$. Age was negatively related to WM, $b = -0.42$, $z = -6.24$, $p < .001$, but, counter our expectations, positively related to attentional control, $b = .34$, 95% CI [.21 - .46], $z = 5.41$, $p < .001$, and, although not significantly, attention fluctuations, $b = .09$, 95% CI [-.06 - .24], $z = 0.97$, $p = .332$. Age was not significantly related to Gf, $b = -.05$, 95% CI [-.19 - .09], $z = -0.62$, $p = .535$. Moreover, attention fluctuations, $b = -.10$, 95% CI [-.25 - .05], $z = -1.40$, $p = .159$, and attentional control, $b = .09$, 95% CI [-.09 - .27], $z = 0.99$, $p = .319$, were not significantly related to Gf. WM was still significantly associated with Gf, $b = .46$, 95% CI [.31 - .61], $z = 6.05$, $p < .001$, after accounting for the two mediators and age. Mediation effects were non-significant.

Mediation Model of Lapses of Attention

The model using lapses of attention revealed similar patterns of results. WM was found to be associated with lapses of attention, $b = .28$, 95% CI [.10 - .46], $z = 3.25$, $p = .001$, indicating that individuals with higher WM performance experience fewer lapses of attention. However, neither lapses of attention, $b = -.10$, 95% CI [-.24 - .03], $z = -1.63$, $p = .100$, nor attentional control, $b = .08$, 95% CI [-.09 - .26], $z = .936$, $p = .349$, were significantly associated with Gf. Consequently, the indirect effect was also not significant, $b = -.01$, 95% CI [-.07 - .02], $z = -.664$, $p = .507$, and the direct effect remained significant after including lapses of attention, attentional control and accounting for age in the model, $b = .46$, 95% CI [.31 - .61], $z = 6.09$, $p < .001$, indicating neither attentional control nor sustained attention explained the relationship between WM and Gf.

3.3.5 Additional and Supplementary Analyses

The findings from both Chapter 2 and Chapter 3 prompted us to conduct further analyses to investigate the relationships between WMC, sustained attention and attention control. These supplementary analyses were motivated by two key findings from those chapters.

First, as shown in Table 2.3, we had found that sustained attention and WMC were related when the task was easy (set size 3), compared to when the task was more difficult (set size 6). This finding led us to question whether the relationship between WMC and sustained attention varies depending on the type of WM measurements used. Specifically, in Chapter 3, we observed a ceiling effect in the updating task, which appeared relatively easier than the other WMC tasks. Based on this, we hypothesized that the correlation between updating and sustained attention would be stronger compared to other WMC tasks.

Second, as shown in Figure 3.3, it seems that sustained attention was more strongly correlated with WM rather than attention control. This raised the question of whether the correlation between sustained attention and binding significantly differed from the correlation between sustained attention and attention control measures. Moreover, these analyses provided an opportunity to examine the maintenance and disengagement theory, as well as binding theory, as alternative explanations for our findings.

These supplementary analyses had two main aims. First, we aimed to compare the relationship between sustained attention and different WM measures by conducting Fisher's r to z tests (Williams' *t*-test). The general result pattern of the Fisher's r to z test revealed that performance in sustained attention was strongly related to performance in the binding task rather than the updating task and continuous reproduction task (see Appendix H).

Second, we aimed to investigate whether sustained attention was statistically strongly correlated with binding rather than attention control. To this end, we once again performed Fisher's r to z tests (Williams' *t*-test) to compare the correlation sustained attention and binding task with the correlation between sustained attention and attention control measures. Overall, the analyses revealed that sustained attention had a significantly stronger correlation with the binding task than with attention control tasks, such as go/no-go, $t(130) = 3.65$, $p < .001$, and Stroop, $t(130) = 2.61$, $p = .009$ (see Appendix I). These findings suggest greater overlap between sustained attention and binding than between sustained attention and inhibition.

3.4 Discussion

This study had two overarching goals addressing the examination of the mechanisms underpinning the relationship between WM and Gf. Therefore, the first goal of the study was to determine whether sustained attention and attention control are the same or different constructs. If they are distinct, the second aim of the study was to investigate whether sustained can explain the relationship between WM and Gf above and beyond attentional control. For this purpose, we assessed each construct with multiple indicators, and operationalised sustained attention as both attention fluctuations and lapses of attention.

First, we established that both attention fluctuations and lapses of attention indicators loaded on their respective factors, which were clearly distinct from the attentional control factor, as expected. The attention fluctuations factor demonstrated a significant relationship with the attentional control factor, $r = .40$, and the lapses of attention factor showed a statistically significant relationship with the attentional control factor, $r = .39$. These findings are consistent with prior research suggesting that attentional control differs from sustained attention (Unsworth et al., 2022). The present study measured attentional control with tasks assumed to assess distraction caused by habits (i.e., Stroop, Simon, and Go/No-go), also referred to as attention restraint (Friedman & Miyake, 2004; Kane et al., 2016; von Bastian et al., 2020). These tasks were used because we found them to have relatively good psychometric properties (as compared to other attentional control tasks (see von Bastian et al., 2020), and are easy to administer across age ranges and different languages. Sustained attention was measured in terms of variability in RTs and an estimate of the τ parameter describing the tail of the RT distribution in the simple RT tasks. When sustained attention is measured using simple RT tasks, where participants are required to press a button as soon as possible in response to a stimulus, it provides information about how response times change over time and how consistently participants are prepared to respond. Our results suggest that failures in the readiness to respond quickly to a stimulus, as indicated by longer RTs and greater RTs variability, differs from, yet is related to attention control, which is consistent with overarching attentional control term (von Bastian et al., 2020).

Mediation analyses with composite scores revealed that, after accounting for age, neither attentional control nor sustained attention explained the relationship between WM and Gf. While these results are consistent with studies suggesting that WM and Gf are significantly unrelated to attentional control and sustained attention (Chuderski et al., 2012; Rey-Mermet et al., 2019; Tsukahara & Engle, 2023), they contradict the maintenance and disengagement theory proposing attentional control explains the relationship between WM and Gf (Shipstead et al., 2014, 2016). However, in contrast to the findings reported by Rey-Mermet et al. (2019) and Tsukahara & Engle (2023), our study revealed that sustained attention and attentional control demonstrated a significant association with WM. One possible explanation is that the process of “maintenance” in WM may reflect individual differences in the ability to consistently pay attention to a simple task, object or event over time. The observed correlation between WM and attentional control suggests individuals with higher WM capacity may also possess stronger attentional control and sustained attention abilities. This heightened state of sustained attention and attentional control could facilitate resistance to interference and distraction during WM tasks, thereby assisting in the effective maintenance of memory items in WM. By filtering out irrelevant stimuli and maintaining focus on relevant information, attentional control supports the successful maintenance of information in WM. These two constructs – sustained attention and attention control – emphasizes the multifaceted nature of attentional processes for the effective maintenance of information in WM.

We found that sustained attention and attentional control were not significantly related to Gf. These results were unexpected. Unsworth et al. (2010) found the relationship between sustained attention and Gf, but our study did not replicate this finding consistent with other studies (Robison & Brewer, 2022; Tsukahara & Engle, 2023). There are two possible explanations for why sustained attention and attentional control were only weakly related to Gf. One possibility is that, because of the absence of external distraction or interference in the sustained attention tasks used in this study do not require disengagement and, therefore, are not correlated with Gf tasks that predominantly emphasize the disengagement of no-longer relevant information. This result seems to be consistent with the maintenance and disengagement theory. However, the surprising and challenging result to maintenance and disengagement theory is the absence of correlation between Gf and attentional control, marked by distraction caused by habits. If the maintenance and disengagement theory were correct, one would expect a relationship between these two constructs. Therefore, the second possibility is that even after accounting for sustained attention and attention control, there appears to be more to the predictive power of WMC than attentional processes. These results challenge the maintenance and disengagement theory. However, the reason behind the varying findings regarding the association between sustained attention and Gf remains unclear. More research will be needed to understand this inconsistency and draw strong conclusions regarding the maintenance and disengagement theory.

The fact that sustained attention and attentional control did not mediate the relationship between WMC and Gf suggests that WM still strongly predicts Gf even after accounting for attentional processes. This led us to consider the specific tasks that contribute to the WM latent variable, particularly the binding task. The binding hypothesis provides an alternative explanation for the correlation between WM and Gf (Oberauer, 2005; Oberauer et al., 2008; Oberauer, 2020) alongside the maintenance and disengagement theory. This hypothesis proposes that individual differences in WMC may reflect individual differences in binding of information in WM. According to this hypothesis, interference between bindings limits WMC. For example, participants are presented with a list of letters to remember while also performing arithmetic operations in a complex span task. Participants need to remember the letters (H, F, Y) while simultaneously solving arithmetic problems. According to the binding theory, successful performance on this task requires the individual letters binding each letter to its corresponding position in the list. Those who are less affected by interference can build more complex representations of structural information. In the fluid intelligence tasks, participants need to find a missing piece in a puzzle, binding involves the integration of multiple pieces of information, such as shape and colour, into a coherent representation within WM. For instance, when attempting to identify the missing piece of a puzzle, individuals need to simultaneously hold in mind the shape and colour of the surrounding pieces while searching for a match. As a result, individuals with higher binding abilities are less affected by interference and they tend to perform better in WM and Gf tasks. This perspective suggests that binding, as a process, may be a crucial mechanism by which WMC supports fluid intelligence.

Interestingly, our supplementary analyses revealed that sustained attention was more strongly related with binding than with other WM tasks or attentional control tasks. This finding suggests that sustained attention might play a role in the process of binding information in WM. According to binding theory, multiple bindings (e.g., remembering several words in different positions) as a form of interference limit WMC (Oberauer, 2020; Oberauer et al., 2016). However, our supplementary findings raise the possibility that failures in sustained attention to bindings may be what limits WMC, potentially leading to increased interference. Moreover, our findings show that sustained attention and attention control are distinct but related processes, with sustained attention showing a greater overlap with binding than with attention control. This could suggest that both the binding theory and the maintenance and disengagement theory may contain elements of truth, but they might be incomplete on their own. According to the maintenance and disengagement theory, sustained attention is a component of attention control. However, our findings suggest that attention is important for binding information in WM, but sustained attention and less so attentional control. Therefore, this result may bring together the binding theory (Oberauer et al., 2008) and the maintenance and disengagement theory (Engle, 2018; Shipstead et al., 2016) in the context of sustained attention, suggesting an alternative explanation, called the binding and maintenance framework for understanding the mechanisms the relationship between WM and fluid intelligence. However, since our study is correlational, we cannot establish a causal relationship between binding and sustained attention. Further research is needed to determine whether sustained attention directly influences the binding process or if other underlying factors contribute to this relationship.

One limitation of the present study was that structural equation modelling used to assess the parallel mediation effect of sustained attention and attentional control on the relationship between WM-Gf did not yield an adequate fit. One potential reason for the overall poor fit of the model could be the relatively small sample size ($n = 133$). Due to the poor fit of the model, mediation analyses were conducted by calculating composite scores for each construct. Future research should aim to employ a larger sample size for structural equation modelling because more sample size may enable to investigate more complex model as in this study. A second limitation was the overall high rates of accuracy on the updating task (overall mean accuracy of 95%). Since the age range of this study was wide (18-85 years old), participants were asked to memorize 3 digits. Therefore, we observed a ceiling effect for the updating task, and as a result, it was not included in the measurement model of the WM latent construct. This implies that participants across a broad age range demonstrate successful performance on the updating task, which comprises three set sizes. To address this limitation, future research should consider incorporating a more varied range of set sizes in the updating task.

3.5 Conclusion

In the present study, we investigated sustained attention by conceptualizing attention fluctuations and lapses of attention and their relationship to performance in WM and Gf tasks above and beyond attentional control. The results of confirmatory factor analyses revealed a clear distinction between sustained attention and attentional control, suggesting that they are separate but related. Furthermore, we found neither sustained attention nor attentional control mediated the relationship between WM and Gf. Interestingly, sustained attention and attention control were associated with WM but not with Gf. These results challenge the assumption that individuals with higher WM performance have better Gf because they are better able to maintain information in WM and better able to disengage information that is no longer relevant.

Chapter 4 – General Discussion

Contributions:

Hakan Atis (conceptualization and writing)

Daniel J. Carroll (supervision)

Claudia C. von Bastian (supervision, conceptualization, review and editing)

4.1 The aims and key findings of the Thesis

This thesis addressed the nature of relationship between individual differences in sustained attention and individual differences in WM and their relationship with complex cognition, in particular attention control and fluid intelligence (Gf). Theoretical accounts propose that the relationship between WM and sustained attention can be explained by two theories: resource depletion (Caggiano & Parasuraman, 2004; Helton & Russell, 2013) and mindlessness (Manly, 1999; Robertson et al., 1997). The resource depletion theory suggests that increased WM load leads to poorer sustained attention due to the depletion of cognitive resources. Conversely, the mindlessness theory posits that lower intrinsic motivation occurs when tasks are under-stimulating and easy, leading to decreased task engagement and attentional lapses. This thesis tested these competing theories. The first objective of the thesis was to examine when sustained attention and WMC are correlated and whether the level of intrinsic motivation of participants can affect the strength of this relationship. The second objective of the thesis was to evaluate whether sustained attention and attention control were a single or two distinct constructs and, if so, whether sustained attention mediates the relationship between WM and Gf above and beyond attention control.

As demonstrated in Chapter 2, moderation analyses showed that the relationship was stronger when the task was easier (i.e. fewer memoranda had to be maintained) for individuals who exerted less effort during the task. Other aspects of intrinsic motivation, specifically perceived competence and interest in the task, and time spent on the WM task did not moderate the relationship between sustained attention and WMC. However, it is noteworthy that as perceived competence increased, the detrimental effect of set size on WM performance not only disappeared but also became positive. Hence, these findings emphasise the importance of intrinsic motivation rather than resource depletion in explaining the poorer sustained attention performance of individuals with lower WMC.

Chapter 3 showed that sustained attention was a distinct construct from attention control at the latent level, especially when sustained attention was measured in the simple RT task which did not require suppression of rare target stimuli. This result is consistent with the finding of Unsworth and colleagues (2021). Furthermore, Chapter 3 examined the broad age range of 18-85 and revealed that age was associated with WM and attentional control but not with sustained attention and Gf. More importantly, after accounting for age, sustained attention and attentional control were related to WM but not to Gf, and neither sustained attention nor attention control mediated the relationship between WM and Gf.

4.2 Strengths of The Thesis

Chapter 2 of the thesis combined individual differences and experimental approaches within a single study to examine possible moderators that influence the relationship between sustained attention and WMC. This combined approach enables the examination of when individual differences in WMC are related to individual differences in sustained attention under different WM set size conditions (3 vs 6) and different time conditions (first half vs second half). Previous research often used a dual task paradigm or thought probes method during WM or sustained attention task performance (Caggiano & Parasuraman, 2004; Helton & Russell, 2011, 2013; Unsworth & Robison, 2016). The additional a secondary task or thought probes may interfere and do not provide information into how these processes vary across individuals under different conditions.

Furthermore, we have used simple RT task, while avoiding the sustained attention tasks with attention control demands such as continuous performance task (CPT) and sustained attention to response task (SART). We used only vigilance paradigms involving fast responses to stimuli rather than detecting or withholding rare target paradigms. This approach allows for a more targeted examination of the relationship between WMC and sustained attention, without the confounding influence of additional attention control demands. Thus, Chapter 2 narrows the scope to specific components of sustained attention (fluctuations and lapses).

Chapter 3 used confirmatory factor analysis focusing on two dependent variables of sustained attention in three simple RT tasks (numbers, shapes and drawings). Previous research has operationalized sustained attention as a latent variable, encompassing a broad range of tasks (i.e., SART, PVT, Choice RT) used to assess this construct (Unsworth, Robison, et al., 2021b). By including three types of simple RT tasks that do not require attention control into to this latent variable, the thesis aims to provide a more precise and targeted assessment of sustained attention and whether attention fluctuations and lapses of attention is different construct from attention control. Thus, we are able to test whether sustained attention, as a basic mechanism, mediates relationship between WM and fluid intelligence. In addition, this provides valuable information about the convergence of binding theory and maintenance disengagement theory.

Furthermore, the thesis' samples were relatively large and diverse. Unlike previous studies that predominantly focused on young university adults, Chapter 3 includes a broader range of participants spanning from 18 to 85 years old. This age-diverse sample not only captures the variability in cognitive abilities across different age groups but also shows individuals with diverse backgrounds and occupations such as retirees, working professionals, and students. In addition, Chapter 2's sample included people from various ethnicities (White = 118, Asian = 109 in Chapter 2), thereby enriching the study with a wide range of life experiences. By including participants from different age ranges and backgrounds, the study enhances the generalizability of its findings, providing information about how WM and sustained attention may vary across the lifespan.

4.3 Theoretical Implications

Chapter 2 did not support resource depletion theory (Caggiano & Parasuraman, 2004; Grier et al., 2003; Head & Helton, 2014; Helton & Russell, 2011), which suggests that sustained attention declines over time due to the depletion of resources. Instead, our results are consistent with mindlessness theory (Manly, 1999; Robertson et al., 1997), which suggests that lapses of attention and attention fluctuations occur due to under-stimulation or lack of intrinsic motivation when doing the task (Seli et al., 2015; Unsworth, Robison, et al., 2021b; Unsworth & Robison, 2020). This study emphasizes that intrinsic motivation individuals bring to WM tasks, may have a stronger impact than resource depletion in explaining the relationship between individual differences in WMC and sustained attention. Individuals who perceived themselves as competent during the WM task showed better WM performance. Furthermore, when the set size (i.e., numbers of memoranda) was low and individuals exerted lower effort, those with experience more lapses of attention exhibited lower WM performance. These findings suggests that effort optimizes the allocation of attention required for challenging tasks through task engagement and reduces readiness response to stimulus for under stimulating tasks. Previous theories mostly focus on sustained attention as an attention control mechanism underpinning of individual differences in WMC and often overlook the contribution of a heightened state of readiness, which distinguishes between attentional control and sustained attention for maintaining information in WM for complex cognition such as Gf.

Therefore, Chapter 3 investigated whether sustained attention as a different construct mediated the relationship between WM and fluid intelligence above and beyond attention control. Chapter 3 revealed that sustained attention did not drive the relationship between WMC and Gf in the absence of interference or external distractions. We found also that attention control did not mediate the relationship between WM and Gf. Thus, Chapter 3 challenges the maintenance and disengagement theory (Engle, 2018; Shipstead et al., 2016), which states that attentional control drives the relationship between WM and Gf through maintenance and disengagement mechanisms. There are also other studies that do not support this theory (Rey-Mermet et al., 2019; Shipstead et al., 2014; Tsukahara & Engle, 2023). These studies found that attentional control was unrelated to the individual differences in Gf as in this thesis. Furthermore, Chapter 3 showed that sustained attention was not significantly related to Gf, although it was related to WM. These results partially overlap with the findings of Tsukahara and Engle (2023) as both studies found that sustained attention was not related to Gf. However, the difference between the two studies arises from in their findings regarding the relationship between sustained attention and WM. While the Tsukahara and Engle (2023) concluded that sustained attention was not significantly related to WMC, the thesis demonstrated a significant association between the two. The significant association observed between sustained attention and WM in our study suggests that sustained attention may play a crucial role in the maintenance aspect of the maintenance and disengagement theory. Specifically, individuals with higher levels of sustained attention may exhibit better abilities to maintain relevant information in WM. However, the lack of a significant relationship between sustained attention and Gf implies that sustained attention may not directly contribute to the broader construct of fluid intelligence. This suggests that while sustained attention may facilitate WM, its impact on Gf may be limited. Taken together, these results speak against the maintenance and disengagement theory (Engle, 2018; Shipstead et al., 2016) and these findings suggest the possibility of other mechanisms above and beyond attention control that could contribute to the relationship between WMC and Gf.

The binding hypothesis provides an alternative explanation for the correlation between WM and Gf (Oberauer, 2005; Oberauer et al., 2008; Oberauer, 2020). This hypothesis proposes that individual differences in WMC may reflect individual differences in binding of information in WM. According to this hypothesis, interference between bindings limits WMC. For example, participants are presented with a list of letters to remember while also performing arithmetic operations in a complex span task. Participants need to remember the letters (H, F, Y) while simultaneously solving arithmetic problems. According to the binding theory, successful performance on this task requires the individual letters binding each letter to its corresponding position in the list. Those who are less affected by interference can build more complex representations of structural information. In the fluid intelligence tasks, participants need to find a missing piece in a puzzle, binding involves the integration of multiple pieces of information, such as shape and colour, into a coherent representation within WM. For instance, when attempting to identify the missing piece of a puzzle, individuals need to simultaneously hold in mind the shape and colour of the surrounding pieces while searching for a match. As a result, individuals with higher binding abilities are less affected by interference and they tend to perform better in WM and Gf tasks.

Researchers proposing the maintenance and disengagement theory have described maintenance in WM as sustained attention over time (Engle et al., 1999a; Tsukahara & Engle, 2023). Therefore, Tsukahara and Engle (2023) anticipated a strong correlation between WM and sustained attention, but contrary to their expectations, they found that sustained attention was not correlated with WM. However, we found the opposite finding. This inconsistency may arise from the tasks used to assess WM. Tsukahara and Engle administered a complex-span and a running-span task. In contrast, in Chapter 2 of this thesis, a binding and continuous reproduction task were used to assess WM. This difference in the tasks used may demonstrate more overlap between sustained attention and binding processes than sustained attention and inhibition. Indeed, our results showed that there was a significant relationship between sustained attention and binding. A heightened state of sustained attention meaning the readiness to respond to a stimulus may contribute activation representation in WM in the broad focus of attention to bind the current context. This heightened state in sustained attention may facilitate the integration of information rather than suppression of irrelevant information. This could potentially reduce interference limiting WMC. That is, when individuals are highly vigilant or experience fewer lapses of attention, they are more likely to effectively bind different pieces of information together in WM than inhibiting irrelevant information. This raises the question of whether there is a causal relationship between these two constructs, despite the correlations observed in our study.

Our second study may provide indirect information about the relationship between binding and sustained attention because for those with a lower level of effort and in set size 6, we found that there was no correlation between sustained attention and WMC. This finding seems consistent with previous research, which suggests that alertness (referring to a heightened state of readiness to respond to stimuli), arousal (referring to the level of physiological and psychological activation or readiness of an individual's central nervous system), and intrinsic motivation to do well the task drive the relationship between WMC and sustained attention (Esterman & Rothlein, 2019; Unsworth & Robison, 2017a, 2017b, 2020). Taken together with the results of Chapter 3 prompts also further contemplation about a heightened state of sustained attention, rather than involving the suppression of irrelevant information. It seems that sustained attention is more related to activation-based models of WM (Cowan, 2017; Cowan et al., 2020; Oberauer & Hein, 2012) rather than attention control model of WMC (Engle et al., 1999a). According to activation-based models of WM, WM is *"the ensemble of components of the mind that hold a limited amount of information temporarily in a* ***heightened state of availability*** *for use in ongoing information processing"* (Cowan et al., 2020, p. 45). When individuals are in a high state of readiness for available use of information or experience fewer lapses of attention, they are more likely to activate representations in the activated part of long-term memory, thereby they are also more likely to effectively bound information in WM. For future research, it would be beneficial to investigate whether sustained attention can causally influence the binding process in WM through experimental methods.

4.4 Limitations of the Thesis

In reflecting on the limitations of the thesis, it is essential to consider how the specific measures and tasks employed to assess WM and related cognitive abilities may have influenced the findings. The choice of tasks may influence the inferences drawn, as varying methodologies to measure related constructs may lead to potential discrepancies in findings. In Chapter 2, we administered a numerical complex span task that captures both storage and processing components of WMC, which is a commonly accepted definition of WMC (Cowan, 2017). In Chapter 3, we utilized different tasks, which are binding, updating and continuous reproduction, to capture various functions of WMC. Previous research has shown that binding, updating and complex span task all loaded onto a general WMC factor (Wilhelm et al., 2013). Consistent with this, our latent variable analysis revealed that binding and continuous reproduction tasks tapped the same WMC factor. The updating task was excluded from the analysis due to a ceiling effect. In addition, both Chapter 2 (using the complex span task) and Chapter 3 (using the binding and continuous reproduction tasks) demonstrated a relationship between WMC and sustained attention. The range of different tasks used renders it unlikely that other measures would yield substantially different findings.

For sustained attention tasks, unlike other sustained attention tasks that capture attention control (e.g., CPT, SART) or measure mind wandering (e.g., thoughts probe methods; see Unsworth et al., 2021), the simple RT tasks we used did not have strong demands for goal maintenance or inhibition of the prepotent response, and they also did not include self-reports to measure mind wandering. While this approach appears to have effectively modelled sustained attention independently of attention control, it may limit the generalizability of the findings to broader concepts of sustained attention. The study by Welhaf and Kane (2022) highlighted the importance of combining both behavioural measures like RT variability and self-report measures such as task-unrelated thoughts to capture the construct of sustained attention more effectively. They argue that each type of measure comes with its own potential biases, but when used together, they can provide a more reliable representation of the sustained attention construct. In this thesis, the exclusion of tasks that assess sustained attention such as CPT or SART as well as measure mind wandering through self-reports may have limited the ability to capture general sustained attention. Future research should aim to model the general ability to sustain attention using a latent variable approach, which can account for measurement error and common variance across tasks. This approach could incorporate simple RT tasks, sustained attention tasks with higher attentional control demands (e.g., SART, CPT), and self-reports of mind-wandering. This would allow for an investigation of whether these components of sustained attention load onto a general sustained attention factor and how this factor relates to WMC, attention control and other cognitive abilities.

For attention control tasks, we utilized Stroop, Simon and go/no-go tasks. The dependent variables were RT differences from conflict tasks and accuracy differences from the discrimination parameter *d'* between hit rates and false rates. In Chapter 3, we found a coherent attention control factor, although the use of difference scores as dependent variables has been criticized in the literature for not always successfully capturing an attention control factor (Unsworth et al., 2021). Still, we did not find a significant correlation between attention control factor and Gf. There are inconsistencies across studies investigating this relationship. Some studies have found a significant relationship between attention control and Gf (Burgoyne et al., 2023; Chuderski & Jastrzębski, 2018; Robison & Brewer, 2022; Tsukahara & Engle, 2023; Unsworth et al., 2024; Unsworth & McMillan, 2014, 2017; Unsworth & Spillers, 2010), while others have not (Chuderski et al., 2012; Rey-Mermet et al., 2019), or have only found a relationship through shared variance with other processes (Shipstead et al., 2014). In studies that found a relationship, the antisaccade task was used with accuracy as the dependent variable, and at least half of the tasks in the relevant factor were based on score differences (a different case from this is Burgoyne et al., 2023 where all dependent variables were difference scores). Conversely, in studies that found no relationship, at least two-thirds of the tasks forming the factor of attention control used score differences as the dependent variable. Given the mixed findings in the literature and the potential limitations of using difference scores as dependent variables, future research should examine alternative methods of measuring attention control that might provide more robust correlations with Gf. One possible approach is to incorporate tasks that directly assess accuracy, such as the antisaccade, Stroop and flanker tasks, which have shown stronger relationships with Gf when accuracy is used as the primary outcome measure (Draheim et al., 2021). Addressing the limitations related to task selection and measurement methods could enhance our understanding of the relationship between attention control and Gf, leading to more consistent and reliable findings in future research.

Another limitation of the thesis is the absence of direct assessments regarding alertness, arousal, and current mood levels (e.g., stress, anxiety, boredom). Previous studies have indicated that individuals tend to experience heightened lapses of attention when their arousal and alertness levels are low, or when they are under stress, bored, anxious, or preoccupied with ongoing concerns (Esterman & Rothlein, 2019; Malkovsky et al., 2012; McVay & Kane, 2010; Sliwinski et al., 2006; Unsworth, Robison, et al., 2021b; Unsworth & Robison, 2020). Furthermore, Unsworth and Robison (2020) found that alertness drives the relationship between WMC and sustained attention. In addition, we did not assess the aspect of mind wandering within sustained attention, assessed through self-reports using the thought probes technique, due to the absence of behavioural measurements. Nevertheless, it still unclear whether alertness, arousal and current model levels moderate the relationship between WMC and sustained attention under varying WM loads. In addition, it is still unknown how these factors related to binding information in WM and dealing with interference. Future research is needed to explore how different aspects (arousal, alertness) of sustained attention are related to WMC under various conditions, thereby providing a more comprehensive understanding of these cognitive processes. Furthermore, further research is needed to better understand how alertness, mind-wandering or arousal related to binding information in WM.

4.5 Conclusion

The doctoral thesis aimed to investigate when sustained attention is related to WMC and whether sustained attention mediated the relationship between WM and fluid intelligence above and beyond attention control. The moderation effect of set size, time-on-task and intrinsic motivation (effort, perceived competence and interest to the task) on the relationship between WMC and sustained was examined in the Chapter 2. Thus, the thesis tested the resource depletion theory (Caggiano & Parasuraman, 2004) and mindlessness theory accompanied by intrinsic motivation (Manly, 1999; Robertson et al., 1997). In the Chapter 3, the thesis investigated the maintenance and disengagement theory (Engle, 2018; Shipstead et al., 2016) by distinguishing between attentional control and sustained attention. Chapter 2 demonstrated that there is no association between WMC and sustained attention when difficulty is high, and effort is low. This finding tentatively suggests support for the mindlessness theory, particularly when accompanied by low effort. Under easy task conditions and low effort, differences in WMC may reflect the readiness responses to stimuli aspects of sustained attention. This highlights the importance of considering both task demands (stimulating or under stimulating) and effort level when investigating the relationship between WM and sustained attention. Chapter 3 revealed that sustained attention is a distinct construct from attention control, and sustained attention and attention control did not mediate the relationship between WM and Gf. Additional exploratory analyses revealed that sustained attention was more strongly related to the binding of information in WM rather than attention control, especially in the go/no-go and Stroop tasks. This suggests that sustained attention shows more overlap with binding than with inhibition. This observation suggests a potential convergence between the binding theory (Oberauer et al., 2008) and the maintenance and disengagement theory (Engle, 2018; Shipstead et al., 2016) in relation to sustained attention. However, further investigation is crucial to fully understand the nature of the relationship between WM and sustained attention, as well as which mechanisms underpinning the relationship between WM and fluid intelligence.

Appendix A

Correlation matrix among all variables without condition (N = 249)

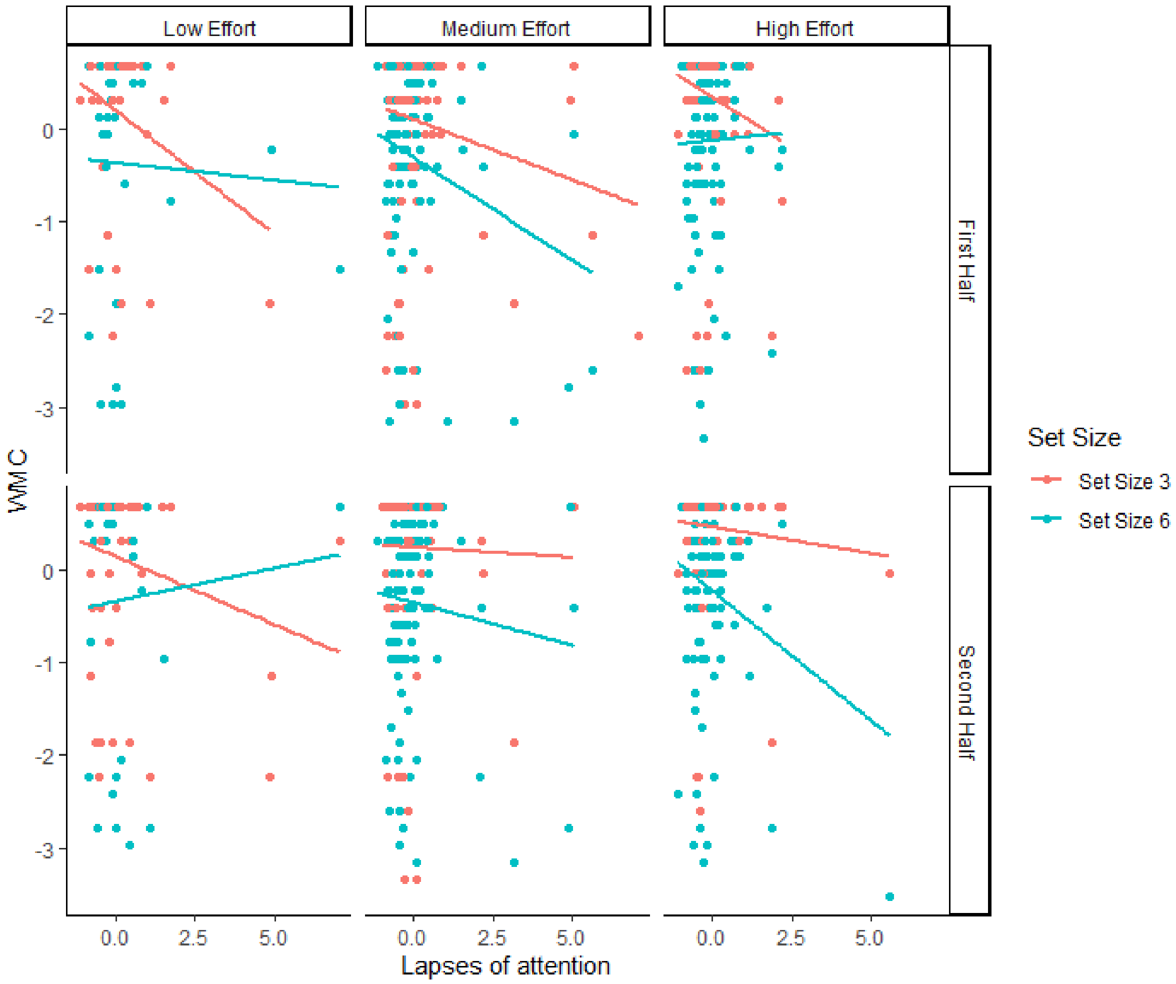
Measures	1	2	3	4	5	6	7
1. WMC	-						
2. τ	**-.14***	-					
3. SD_{RT}	-.11	**.93*****	-				
4. NFC	.08	-.06	-.05	-			
5. Effort	.06	-.10	**-.15***	.05	-		
6. Perceived Competence	**.52*****	.04	.06	.09	.11	-	
7. Interest	**.31*****	-.02	.03	.12	.07	**.53*****	-

Note. Bold correlations are significant. WMC = working memory capacity; τ = tau parameter from Ex-Gaussian; SD_{RT} = standard deviation of reaction time; NFC = need for cognition.

***$p < .001$, **$p < .01$, *$p < .05$.

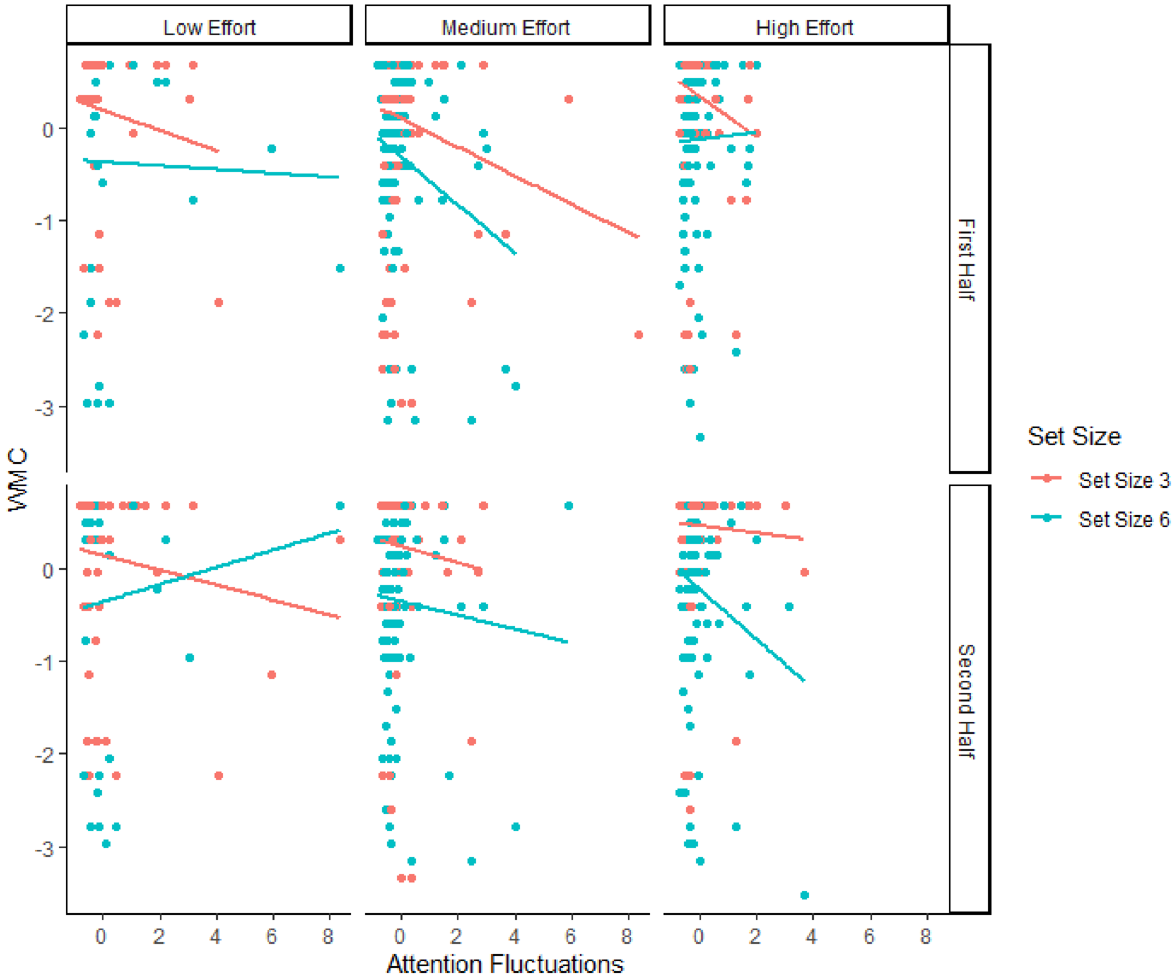
Appendix B

The moderation effect of set size, time-on-task and effort on the relationship between τ and WMC



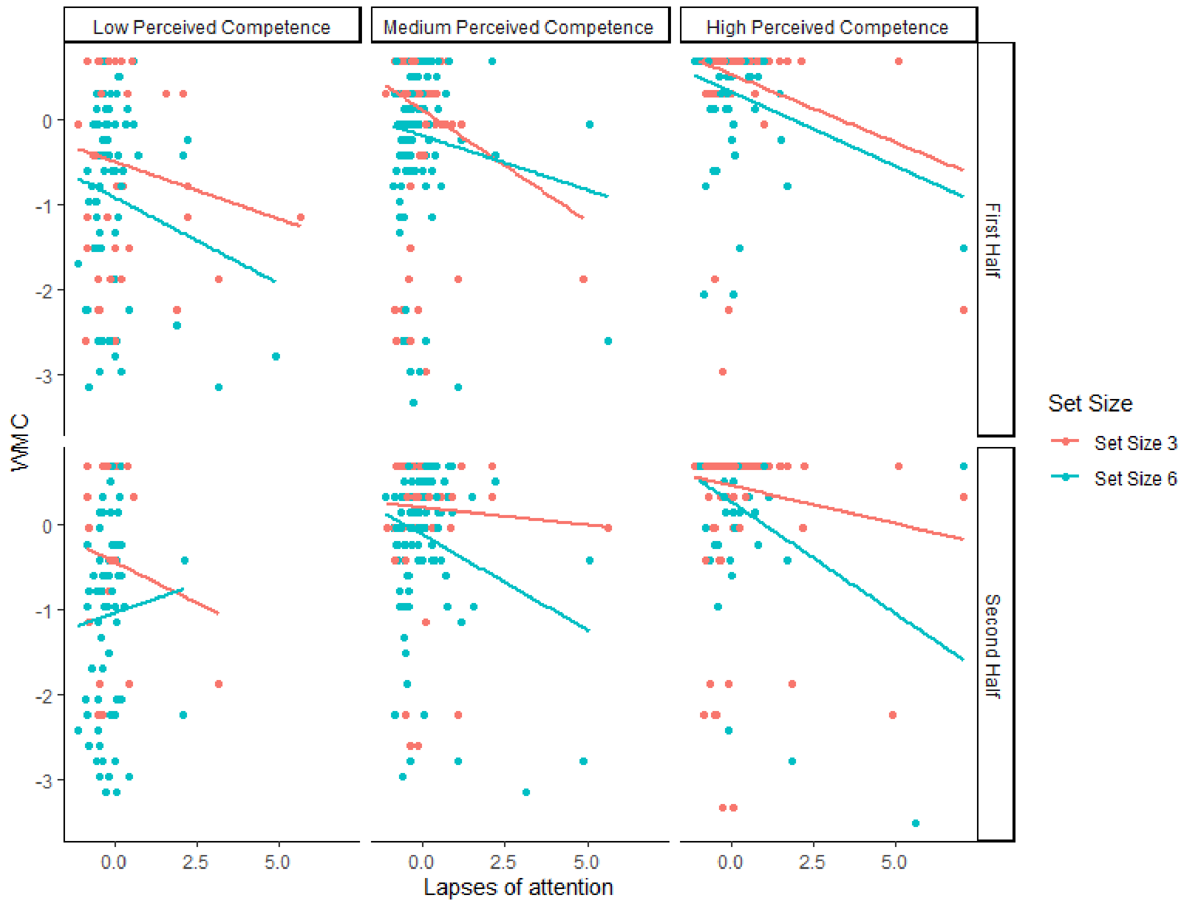
Appendix C

The moderation effect of set size, time-on-task and effort on the relationship between SD_{RT} *and WMC*



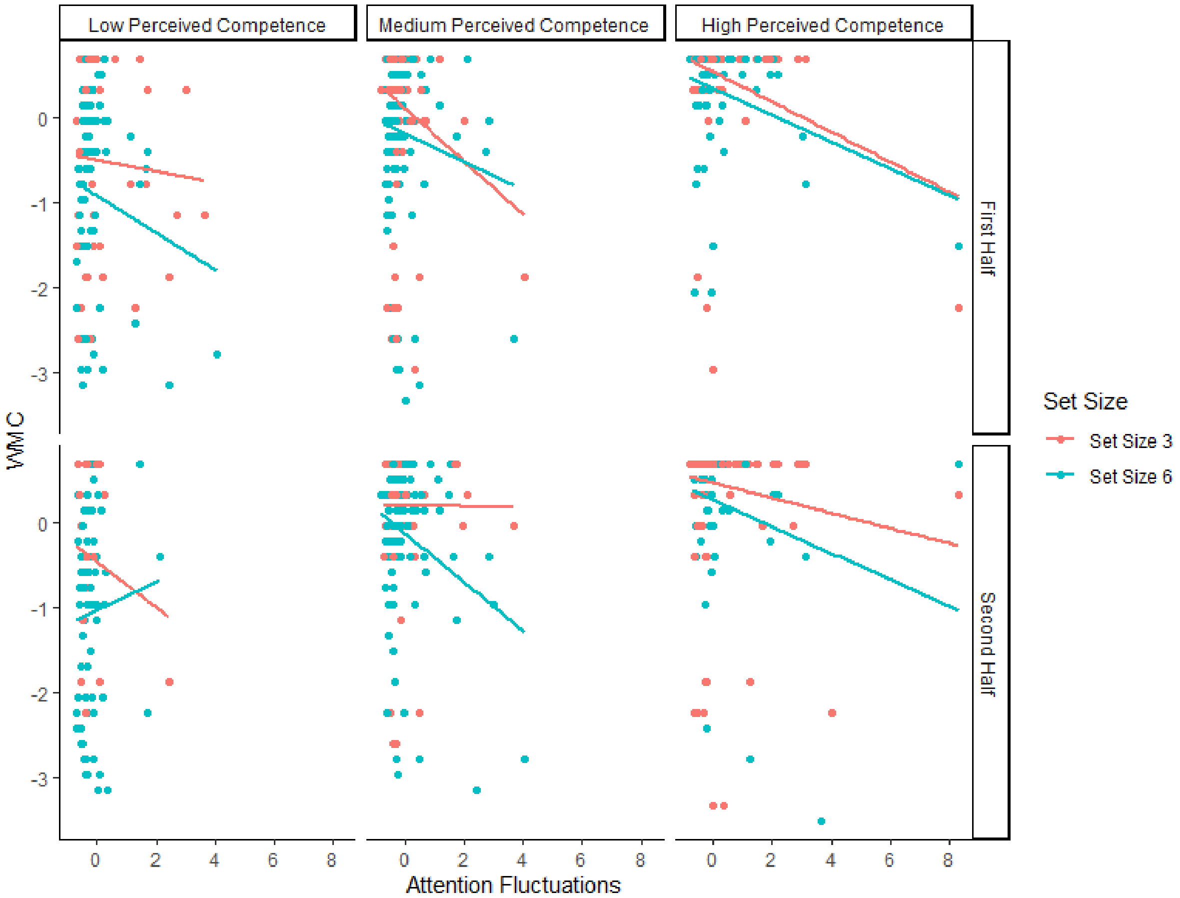
Appendix D

The moderation effect of set size, time-on-task and perceived competence on the relationship between τ and WMC



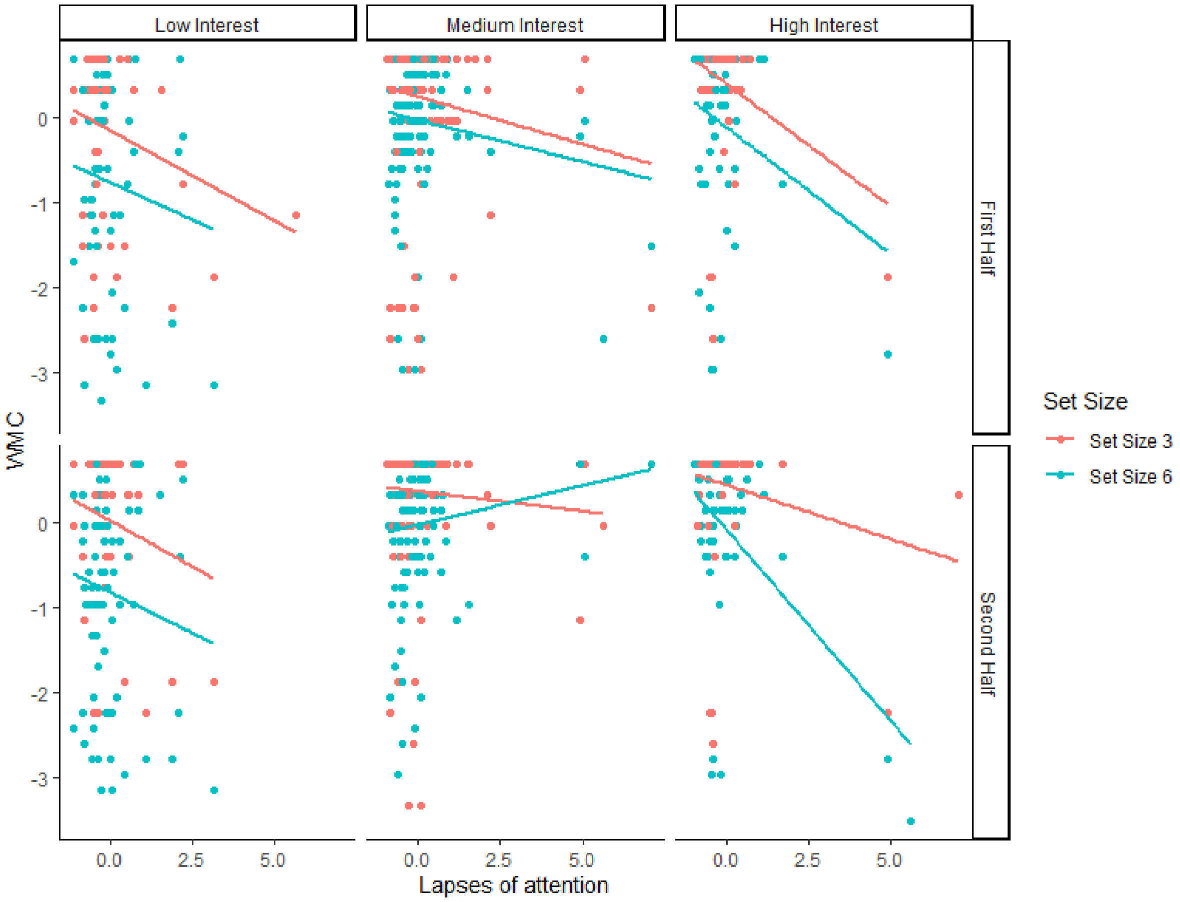
Appendix E

The moderation effect of set size, time-on-task and perceived competence on the relationship between SD_{RT} and WMC



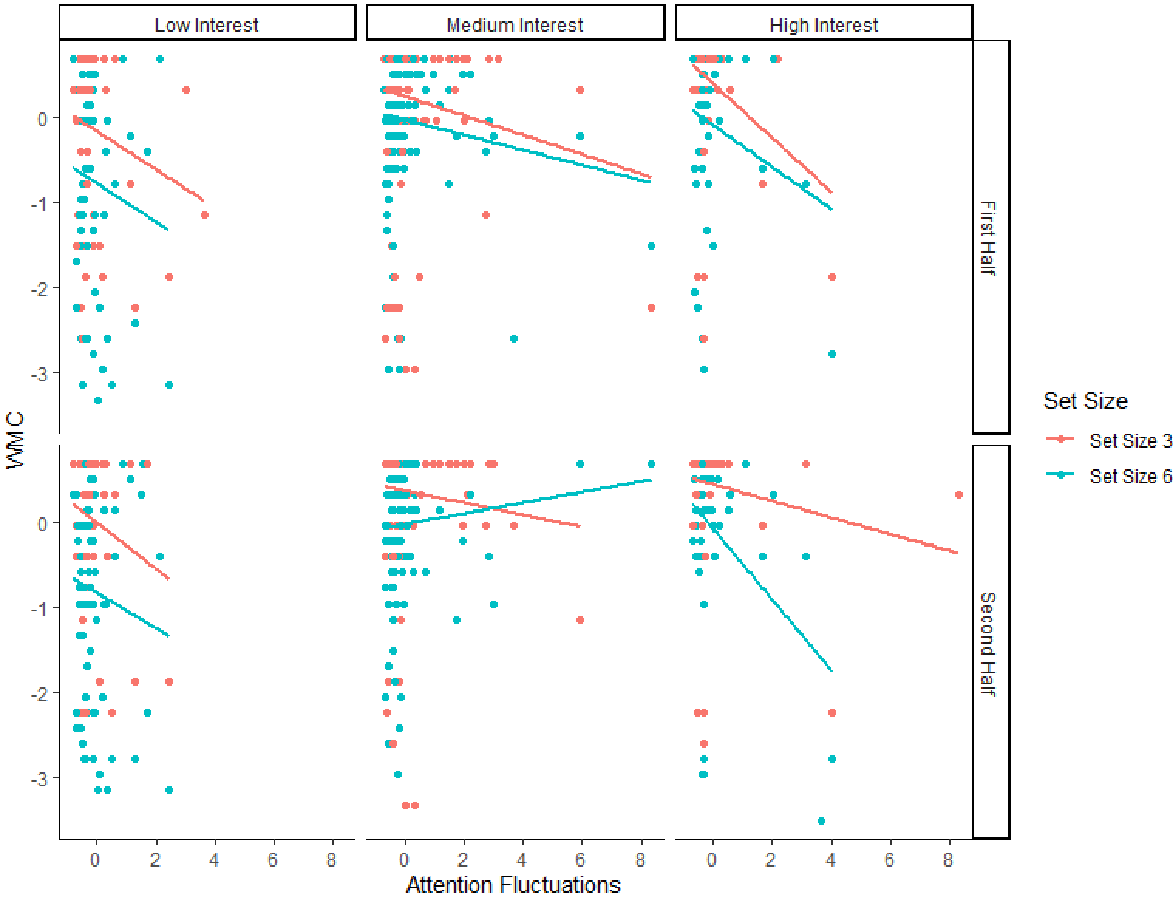
Appendix F

The moderation effect of set size, time-on-task and task interest on the relationship between τ and WMC



Appendix G

The moderation effect of set size, time-on-task and task interest on the relationship between SD_{RT} and WMC



Appendix H

Comparison of Correlations between Sustained Attention and Binding versus Sustained Attention and Other Working Memory Measures

Measures	Binding	Updating	Continuous Reproduction	*t*	*p*
τ N	-0.247***	-0.029	-	2.44	0.015(two-tailed)
τ N	-0.247***	-	-0.074	2.44	0.963(two-tailed)
τ N	-	-0.029	-0.074	-4.55	0.649
SD_{RT} N	-0.162	0.013	-	1.92	0.028(one-tailed)
SD_{RT} N	-0.162	-	-0.022	1.93	0.027(one-tailed)
SD_{RT} N	-	0.013	-0.022	-0.35	0.726
τ S	-0.294***	-0.096	-	2.23	0.027(two-tailed)
τ S	-0.294***	-	-0.213*	1.14	0.253
τ S	-	-0.096	-0.213*	-1.18	0.237
SD_{RT} S	-0.258**	-0.055	-	2.26	0.012(one-tailed)
SD_{RT} S	-0.258**	-	-0.253**	0.065	0.474
SD_{RT} S	-	-0.055	-0.253**	-2.02	0.045(two-tailed)
τ D	-0.324***	-0.083	-	2.75	0.006(two-tailed)
τ D	-0.324***	-	-0.218*	1.52	0.128
τ D	-	-0.083	-0.218*	-1.36	0.173
SD_{RT} D	-0.248**	-0.035	-	2.75	0.006(one-tailed)
SD_{RT} D	-0.248**	-	-0.113	1.89	0.029(one-tailed)
SD_{RT} D	-	-0.035	-0.113	-0.77	0.438

Note. SD_{RT} N = standard deviation of reaction time in the numbers task; SD_{RT} S = standard deviation of reaction time in the shapes task; SD_{RT} D = standard deviation of reaction time in the drawings task; τ N = tau in numbers task; τ S = tau in shapes task; τ D = tau in drawings task .***$p < .001$, **$p < .01$, *$p < .05$.

Appendix I

Comparison of Correlations between Sustained Attention and Binding versus Sustained Attention and Attention Control Measures

Measures	Binding	Go/No-Go	Simon	Stroop	t	p
τ N	-0.247***	-0.040	-	-	1.67	0.049(one-tailed)
τ N	-0.247***	-	-0.242**	-	0.04	0.963
τ N	-0.247***	-	-	-0.142	0.83	0.405
SD_{RT} N	-0.162	-0.139	-	-	0.18	0.853
SD_{RT} N	-0.162	-	-0.254**	-	-0.84	0.401
SD_{RT} N	-0.162	-	-	-0.180*	-0.14	0.888
τ S	-0.294***	0.007	-	-	2.44	0.015(two-tailed)
τ S	-0.294***	-	-0.191*	-	0.95	0.339
τ S	-0.294***	-	-	-0.177*	0.93	0.350
SD_{RT} S	-0.258**	-0.128	-	-	1.04	0.296
SD_{RT} S	-0.258**	-	-0.212*	-	0.42	0.672
SD_{RT} S	-0.258**	-	-	-0.226**	0.25	0.802
τ D	-0.324***	0.117	-	-	3.65	0.000(two-tailed)
τ D	-0.324***	-	-0.154	-	1.58	0.114
τ D	-0.324***	-	-	0.003	2.61	0.009(two-tailed)
SD_{RT} D	-0.248**	0.078	-	-	2.63	0.009(two-tailed)
SD_{RT} D	-0.248	-	-0.169	-	0.71	0.474
SD_{RT} D	-0.248	-	-	-0.075	1.37	0.172

Note. SD_{RT} N = standard deviation of reaction time in the numbers task; SD_{RT} S = standard deviation of reaction time in the shapes task; SD_{RT} D = standard deviation of reaction time in the drawings task; τ N = tau in numbers task; τ S = tau in shapes task; τ D = tau in drawings task .***$p < .001$, **$p < .01$, *$p < .05$.

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