Handwriting and working memory: the role of memory and other cognitive factors in the performance of psychomotor skills such as handwriting and drawing

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Handwriting and Working Memory

The Role of Memory and other Cognitive Factors in the Performance of Psychomotor Skills such as Handwriting and Drawing

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19/04/2016
For Mum
I certify that the work presented in this thesis is, to the best of my knowledge and belief, original, except as acknowledged in the text, and that the material has not been submitted, either in whole or in part, for a degree at this or any other university.

I acknowledge that I have read and understood the University's rules, requirements, procedures and policy relating to my higher degree research award and to my thesis. I certify that I have complied with the rules, requirements, procedures and policy of the University (as they may be from time to time).

Signed …………………………………………. Date 19/04/2016………………….
“If men learn this, it will implant forgetfulness in their souls; they will cease to exercise memory because they rely on that which is written, calling things to remembrance no longer from within themselves, but by means of external marks. What you have discovered is a recipe not for memory, but for reminder…” (Plato, c. 429-347 B.C.E as cited in Hackforth, 1952, pp 157).
Working memory (WM) and handwriting use common resources. In this dissertation, I explore how handwriting reduces WM performance. I uniquely investigate how the verbal and motor aspects of handwriting separately contribute to a reduction in WM performance. The general methodology utilised a verbal serial recall task, typically with input via listening (i.e. auditory presentation of the word lists), compared to listening along while simultaneously handwriting the words during input, or performing nonverbal pseudo-handwriting movements or drawing movements. The results within the thesis are predominantly interpreted within the Time-Based Resource-Sharing (TBRS) model of WM (Barrouillet & Camos, 2007) which states that forgetting is due to the time related decay of information, suggesting that only one task can be performed at any time.

In experiment 3.1, I confirm that handwriting reduces verbal serial recall compared to listening and reading, while also identifying that different mechanisms are involved when processing verbal information during reading, writing, and listening tasks. In experiment 4.1 and 4.2, I uniquely identify that that the motor component of handwriting is reducing verbal serial recall with little additional reduction in performance due to the verbal component. In the analysis in 5.1 and experiment 5.2, I found that there is no consistent relationship between handwriting kinematics and verbal serial recall. In experiment 5.3, I found that the kinematic measures of handwriting fluency do not improve when performed independently of a verbal serial recall task. It is argued that there is little to no trade-off, with handwriting fluency being maintained at the cost of WM performance. In experiment 6.1, I demonstrated that by increasing the attentional load of a secondary tapping task that an incremental decrease is elicited across both handwriting kinematics and verbal serial recall. In experiment 7.1, I determine that a reduction in verbal serial recall occurs even when performing fine motor movement tasks that are dissimilar to writing (e.g., drawing shapes). Specifically, concurrent continuous movements
reduce verbal serial recall performance more than discrete movements or listening alone. It is argued that this is because the continuous movements capture attention for relatively longer periods compared to discrete movements. I argue that the reduction in working memory performance while handwriting is due to attention being captured by the planning and performing of the motor components of handwriting. A similar effect is also found while drawing, supporting the claim that motor movements reduce working memory performance. The concluding chapters show how the results fit well within TBRS model.
Abstract

Working memory (WM) and handwriting use common resources, and when performed concurrently WM performance can suffer. In this dissertation, I explore how handwriting reduces WM performance. I uniquely investigate how the components of handwriting (verbal, motor) contribute to a reduction in WM. The general methodology utilised a verbal serial recall task with words recalled after listening to word lists with no concurrent secondary task, or listening to the words while simultaneously performing handwriting, nonverbal pseudo-handwriting or drawing movements. My key finding is that the motor component of handwriting reduces WM performance with little additional reduction due to the verbal component.
Chapter Summary

Working memory (WM) tasks and handwriting tasks use common resources, and when performed concurrently WM performance can suffer. In this dissertation, I explore how handwriting reduces WM performance. I uniquely investigated how the verbal and motor aspects of handwriting separately contribute to a reduction in WM performance. The results within the thesis are predominantly interpreted within a Time-Based Resource-Sharing (TBRS) model of WM (Barrouillet & Camos, 2007) which states that forgetting is due to the time related decay of information, suggesting that only one task can be performing at any time. Additionally, the model indicates that tasks that capture attention for longer periods tend to decrease performance.

In the first Chapter, I review the literature surrounding the different models of working memory and handwriting. I show that within the framework of handwriting and the Time-Based Resource-Sharing (TBRS) model of WM, it is plausible that performing handwriting will reduce performance on a simultaneous WM task. In Chapter 2, I provide an overview of methodology that has been used to test verbal working memory and handwriting. The general methodology utilised a verbal serial recall task, typically with input via listening (i.e. auditory presentation of the word lists), compared to listening along with simultaneously handwriting the words during input, or performing nonverbal pseudo-handwriting movements or drawing movements.

In Chapter 3, I confirm that handwriting reduces verbal serial recall compared to listening and reading. Additionally, the pattern of recall changed across the serial position curve between conditions. This suggests that different mechanisms are involved when processing verbal information during reading, writing, and listening tasks. In Chapter 4, two experiments show that handwriting and pseudo-handwriting (i.e., combinations of “el” e.g., elele) reduce verbal serial recall compared to just listening. These results show that the serial recall is similar
when performing concurrent handwriting and pseudo-handwriting movements, with both reducing verbal serial recall compared to listening alone. This provides robust evidence that the motor component of handwriting is reducing verbal serial recall with little additional reduction in performance due to the verbal component of handwriting. In Chapter 5, three experiments were conducted to further investigate whether a relationship exists between handwriting kinematics and verbal serial recall. The correlative analyses did not find a relationship between handwriting kinematics and the proportion of words recalled. Chapter 5 also investigated the possible trade-off in performance between the handwriting task and the recall task. This showed that the kinematic measures of handwriting fluency do not improve when performed independently of a verbal serial recall task. In contrast, the cognitive requirements needed to write appear to capture and hold attention, reducing serial recall performance. It is argued that here there is little to no trade-off, with handwriting fluency being maintained at the cost of WM performance.

Chapter 6 demonstrates that by increasing the attentional load of a secondary tapping task an incremental decrease is elicited across both handwriting movement fluency and verbal serial recall. This supports the argument that when cognitive load increases, performance on all tasks suffers if all tasks are to be maintained to at least a minimal level of performance. In Chapter 7 I determine that a reduction in verbal serial recall occurs even when performing fine motor movement tasks that are dissimilar (qualitatively and kinematically) to writing (e.g. drawing shapes). Additionally, concurrent continuous movements reduce verbal serial recall performance more than discrete movements or listening alone. It is argued that this is because the continuous movements capture attention for relatively longer periods compared to discrete movements.

In Chapter 8 I develop a model to predict the pattern of verbal serial recall through the proportion of time for decay, activation, and rehearsal. The final chapter is the general discussion and summary of the key findings. I argue that the reduction in working memory
performance observed in this thesis is due to attention being captured by the planning and performing of the motor components of handwriting and drawing.
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# Abbreviations

<table>
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<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>Average absolute velocity</td>
<td>AAV</td>
</tr>
<tr>
<td>Average normalized jerk</td>
<td>ANJ</td>
</tr>
<tr>
<td>Average number of strokes</td>
<td>ANS</td>
</tr>
<tr>
<td>Average Stroke Duration</td>
<td>ASD</td>
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<tr>
<td>Average Stroke Size</td>
<td>ASS</td>
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<tr>
<td>Dorsolateral prefrontal cortex</td>
<td>DLPFC</td>
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<td>Prefrontal cortex</td>
<td>PFC</td>
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<td>Serial Position</td>
<td>SP</td>
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<tr>
<td>Time-based resource-sharing model</td>
<td>TBRS</td>
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<td>Working Memory</td>
<td>WM</td>
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Chapter 1 – Literature Review
My purpose for this thesis is to explore and further contribute to the existing knowledge on the interfering nature of handwriting on working memory (WM) performance. From previous literature (e.g., Berninger & Richards, 2012; Kellogg, Olive, & Piolat, 2007; Kellogg, 1996, 2001; McCutchen, 1996; McCutchen, 2000; Olive, 2004; Peverly, 2006; Peverly, Garner, & Vekaria, 2013; Piolat, Barbier, & Roussey, 2008; Piolat, Olive, & Kellogg, 2005) it is evident that writing can contribute to a reduction in WM performance in adults and children. This has been attributed to individual differences in WM capacity and handwriting competency, fluency, as well as identifying the limited capacity of WM to process all aspects of the handwriting process. A majority of these studies have looked at a relationship between WM span and handwriting during separate tasks. The aim of my thesis is to identify how handwriting reduces WM performance in adult participants when the two tasks are completed simultaneously.

Within this thesis, when I use the term handwriting in reference to my research, I refer to the lower-level demands of writing. Handwriting requires an interaction of multiple cognitive processes such as the verbal requirements needed to spell words and form legible sequences of letters, and to transform phonemes to graphemes (i.e., sounds to letters). Handwriting also refers to the motor requirements needed to form letters and words, as well as ensuring the correct spatial sequence of letters (Berninger & Graham, 1998). Traditionally, writing refers to the ability to produce large amounts of text, this includes the production of sentences, paragraphs, and essays. This typically involves the generation of contextual meaning and greater semantic representation to form logical sequences of ideas. Within the literature, there is no real consistency with these terms, and they are sometimes used interchangeably. However, within this thesis, unless otherwise indicated, I use the term writing when referring to previous research that has investigated the production of large amounts of text, while handwriting refers to the lower-level demands needed to produce written text. As such, all the experiment within this thesis investigate handwriting.
It is apparent that handwriting requires both a verbal component to produce the language aspect of handwriting (sounds and spelling) and visual and spatial components to produce the handwriting movements (to form the letters, words, and sentences; Kellogg, 1996). What has not yet been identified in the literature, is what mechanism of handwriting is contributing to the reduction of WM performance. My aim for this thesis is to explore this question. In the experiments, I will firstly aim to identify if handwriting reduces WM performance when performed simultaneously with a verbal serial recall task. If so, I will then pull apart the different components of handwriting to identify which mechanism (verbal or motor movements) is contributing to the reduction in performance. In the closing experiments of the thesis I will begin to outline and attempt to identify which cognitive mechanisms (e.g., attention) are contributing to the reduction in WM performance while handwriting.

1.1 A Review of Working Memory: Models and Theories

Working memory is the limited capacity system that is utilised for temporarily processing, manipulating, storing, and retrieving information to help complete cognitively demanding tasks (Baddeley, 2000, 2003, 2012). It is essential for our ability to adapt to circumstances and certain environments where our natural instinctual responses are insufficient to overcome problems efficiently. WM enables us to integrate sensory input from many different modalities to produce an outcome appropriate for the circumstance. A central feature of WM is trace decay, whereby, memory begins to decay when it is not activated, rehearsed, or allowed time to be refreshed. The decay of memory occurs over a relatively short period (e.g., 2-3 seconds; Baddeley & Hitch, 1974; Cowan, 2010) unless it is refreshed in some way (e.g., sub-vocal rehearsal, or focus of attention).

Although I have referred above to trace decay, I am aware that there is some debate about whether forgetting in WM is due to interference (e.g., Lewandowsky, Oberauer, &
Brown, 2009) or decay (e.g., Portrat, Barrouillet, & Camos, 2008). However, as the key model I employed within the thesis is Barrouillet & Camos’ (2007) time-based resource-sharing (TBRS) model of working memory, I typically interpret the results as a time-related decay of memory. When I use the term *interference* I am referring to handwriting interfering with the ability to switch resources back to WM processes. Nonetheless, I argue that this interference results in a decay of memory.

The development of the multi-component model of WM (Baddeley, & Hitch, 1974) has inspired more than 40 years of research within this field. Within this literature review I will cover key models and theories that have shaped WM research before outlining the recently proposed TBRS model of WM (Barrouillet & Camos, 2007) and the emergent property model of WM (Postle, 2006).

1.1.1  *The multi-component model of working memory*

In recent years, research has begun to move away from the standard model of WM (Baddeley, 1986; Baddeley, & Hitch, 1974; Goldman-Rakic, 1987). This model assumes that all WM processes are subject to processing and manipulation within the pre-frontal cortex. I will later provide evidence that shows this to be neurologically improbable. Nonetheless, the components and core assumptions of the model are worth outlining to prepare the foundation for more recent developments.

Baddeley’s (2000) multi-component model of WM consists of a central executive and three subsystems (the phonological loop, the visuo-spatial sketchpad, and the episodic buffer) which are able to draw information from long term memory. Figure 1.1. Shows a conceptualisation of the multi-component model of WM.
Figure 1.1 Baddeley’s (2000) multi-component model. The lines represent the flow of information between the different sub-systems.

**Central Executive**

The central executive is the governing system of WM. It is responsible for allocating attention to the different subsystems based on the type of sensory information that is processed within WM. Further to this, the central executive is able to split attention between multiple tasks allowing the simultaneous input of different types of sensory information (Acheson & MacDonald, 2009; Baddeley, 2003, 2012; Baddeley & Larsen, 2007). For example, if you were asked to focus on the colour of a car, the central executive is able to focus attention on the car colour. If you were then asked to listen to a sentence while still attending to the car colour, the central executive is able to allocate attentional resources to perform both tasks. However, the assumption that the central executive can perform dual tasks simultaneously has been criticised (e.g., Barrouillet & Camos, 2007; Cowan, 2001; Oberauer,
The main role of the central executive is to allocate resources to the sub-systems appropriately. A core assumption of the central executive (that is consistent across models) is that it is incapable of storage but merely directs how and when attention will be allocated.

**Phonological Loop**

The phonological loop is a temporary store for auditory stimuli such as language, speech, reading, and other sounds (Baddeley, 2000, 2003; Baddeley, & Larsen, 2007). It allows verbal information to be maintained for a brief period (Baddeley, 2012). The core assumptions of the phonological loop indicate that the maintenance of verbal information is achieved through sub-vocal or vocal rehearsal. The performance of the subsystem is dependent on what Baddeley (2012) outlined as the word length effect, similarity effect, lexical effects, and articulatory suppression as discussed below. For example, while listening to words, the verbal information is heard and can be stored directly in the phonological loop as it is phonologically coded (Baddeley & Larsen, 2007; Haenggi & Perfetti, 1992). However, this process becomes more complicated when reading. When reading, information must be converted into a phonological code before being temporarily stored in the phonological loop (Baddeley, 1997; Sadoski & Paivio, 2004). This is achieved through the articulatory control process by sub-vocalising the written material (Lewandowsky & Farrell, 2006; Page & Norris, 1998; Tan & Ward, 2008).

The retrieval of verbal information is limited by the length of the items and the similarity of the items. This is seen through the word length effect (Hulme, Neath, Stuart, Shostak, Surprenant, & Brown, 2006) this suggests the length of the word can determine how well items are recalled. Baddeley (2000) argues that the number of items in the list is not the key variable but the items themselves. Baddeley suggest item length plays a significant role in determining the capacity of WM and the word list used. For example, if short words were
used consisting of one syllable (e.g., cat, dog, bird, bat, snake, and bear) they would be remembered easier than words consisting of multiple syllables and letters (e.g., elephant, hippopotamus, rabbit, tiger, kangaroo, and alligator). Baddeley indicated that trace decay is responsible for the decline in memory, and to prevent trace decay, items must be refreshed through sub-vocal rehearsal. The longer it takes a word to be sub-vocally rehearsed, the less likely it will be retained (the more likely it will have decayed before it could be refreshed).

The reason why there is superior recall for short words, is because they can be processed and refreshed relatively quicker than long words. Essentially, Baddeley suggests that WM is limited by trace decay, the limits of WM are confined by the ability to refresh items. However, this has been criticised by other WM models (see Cowan’s, 1995, 2001 models below) indicating WM is limited to a specific number of items (or chunks). Despite these criticisms, Baddeley (2000) introduced the episodic buffer, which appears to include a similar process to the chunking of items outlined in Cowan’s (2001) model.

Another aspect of word lists to consider which was outlined in Baddeley and Hitch’s (1974, Baddeley, 1986) original paper is the similarity effect. That is, items that are phonologically similar (e.g., cat, bat, sat, rat, mat, and fat) will not be recalled as efficiently as dissimilar words (e.g., cat, bag, rib, won, top, and sea). This is because words are coded phonologically, and as such, phonologically similar words are not recalled as well as phonologically dissimilar words (also see more recent work by Baddeley, 2012; Spurgeon, Ward, & Matthews, 2014). This could be due to similar words sharing a phonological code, and results in a “shared” decay, which occurs relatively quicker than dissimilar words (Mueller, Seymour, Kieras, & Meyer, 2003; Posner & Konick, 1966). Alternatively, when similar words are to-be-remembered, retrieval of those items becomes difficult because the words cannot be phonologically disentangled from one another (Hulme et al., 1997; Mueller, Seymour, Kieras, & Meyer, 2003; Nairne, 1990).
Lexical effects are also of concern during WM tasks, Baddeley and Hitch’s original model did not account for the role of long term memory in WM and lexical effects were not considered a problem. Lexical effects refer to how prior knowledge of words (e.g., an individual’s lexicon) contribute to the representation of words in WM. For example, familiar words are recalled better than less familiar words (Hulme, Maughan, & Brown, 1991). The criticism of not accounting for lexical effects or long term memory in the model led to a revised multi-component model (Baddeley, Gathercole, & Papagno, 1998). This advancement was necessary to explain that long-term memory aids in WM processing and maintenance, specifically when considering lexical effects. The methods chapter (Chapter 2) outlines how controlling word familiarity, imagability, concreteness, and word frequency are important to control for lexical, semantic, and similarity effects.

Articulatory suppression may also hinder retrieval. This occurs when a secondary verbal task is performed concurrently with a verbal WM task (Acheson, Postle, & MacDonald, 2010; Baddeley, 2002; Baddeley, 2012; Baddeley, & Larsen, 2007; Cowan, 2001; Gathercole, 2008). Essentially the task may draw attentional resources away from the rehearsal process as it is more cognitively demanding and the central executive is unable to devote adequate attention to both tasks. Cognitively demanding refers to tasks that require or utilise the limited capacity of working memory, tasks that require more resources are considered to be relatively more cognitively demanding (Braaksma & Council, 2015; Burnham, 2010; Chandler & Sweller, 1991; Cowan, 2005; Crescentini, Marin, Del Missier, Biasutti, & Shallice, 2011; Eysenck, Derakshan, Santos, & Calvo, 2007; Holmes & Gathercole, 2013; Lindenberger, Marsiske, & Baltes, 2000; Peverly et al., 2013; Podell et al., 2012; Swanson & Berninger, 1996; Sweller, Ayres, & Kalyuga, 2011; Titz & Karbach, 2014) For example, during a memory task, repeating a word (e.g., “The”) aloud while reading will interfere with the processing of the written material, making it more difficulty to complete.
This is due to the phonological loop’s inability to process multiple phonological codes simultaneously (Baddeley, 1976, 1986, 2000, 2012).

Visuo-spatial Sketch Pad

The visuo-spatial sketchpad consists of two components. The first component is a visual storage system to process objects in reference to how they fit within the current environment or mentally formed images. An example of this is retrieving the spatial location of an item that was placed within a visual field, or creating a mental image of an object (Baddeley, 2000, 2002, 2012; Chen & Cowan, 2009; Logie, 1995; Logie, 2011; Neath, & Surprenant, 2003). The visual system is also responsible for identifying specific characteristics of visual objects. For example, studies in change blindness indicate that we are unable to identify changes in our environment if we are not attending to them (Baddeley, 2003). The second component is a spatial storage system, which is used for processing sequential items within a spatial domain.

The spatial component is responsible for processing sequential movements and patterns, for instance, being shown a path through a maze, then having to recall that information to perform or give directions through the maze. There have been suggestions indicating that the visuo-spatial sketchpad may play a specific role in kinematics and learning movements (Baddeley, 2012, Smyth & Peddelton, 1990). It is responsible for how we perceive and process information within our visual environment, such as our ability to attend to objects, shapes, and movement.

The visuo–spatial sketchpad has not been without criticism with recommendations for the subsystem to be separated into a visual and spatial domain. Evidence from adult and child studies have shown that visual and spatial information appear to be processed differently (Baddeley, 1996; Baddeley, 2012; Holmes, Adams, & Hamilton, 2008; Klauer & Zhao, 2004; Pickering, 2001). This has led to suggestions of a fractionation of the visual and spatial
components with evidence supporting that there is clear distinction between the two processes (Baddeley, 2012; Klauer & Zhao, 2004). For example, it has been found that the rate of learning in children was significantly different for visual and spatial working memory (Logie & Pearson, 1997). There is also clear neurological evidence to show that visual and spatial information is processed in different neural regions and pathways (Baddeley, 2012; Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Smith & Jonides, 1997).

**Episodic Buffer**

The episodic buffer has been the most significant addition to the multi-component model since its conception. The episodic buffer is limited in capacity and is multi-coded, as it is able to store information from the different WM subsystems as well as draw information from long term memory (Baddeley, 2000, 2012; Baddeley, & Larsen, 2007). Consistent with the other WM components the central executive governs the functioning of the episodic buffer. The central executive is able to retrieve information from the episodic buffer in order to manipulate, transform, and present the information within conscious awareness (Baddeley, 2000, 2012; Baddeley, & Larsen, 2007). As mentioned, the episodic buffer acts as a temporary storage system where the phonological loop, visuo-spatial sketch pad, and long-term memory are able to interact. Information can be integrated and made available for the central executive to execute cognitive tasks. This suggests the episodic buffer plays a significant role in collating information and making it available to the central executive to complete complex cognitive tasks (Logie, 2011; Peverly, 2006; Repovs & Baddeley, 2006). The addition of the episodic buffer attempted to answer a flaw in the multi-component model, through the integration and acknowledgment of the relationship between WM and long-term memory. However, others suggest that the concept of a separate cognitive subsection to temporarily store information for other storage areas is theoretically and neurologically improbable (Rose & Craik, 2012).
Baddeley and Hitch’s multicomponent model of WM was an integral development in our understanding of how we process, integrate, and recall complex information. While there have been amendments made to the model, it appears that modern theories have begun to move away from the suggestion of a multi-component model and the assumptions that were made. Theories that are more recent are outlined below and have a stronger focus on the role of attention and the limited availability of resources.

1.1.2 Cowan’s embedded process theory

Cowan’s (1995, 2001) embedded process theory argues that WM is simply the activation of long-term memory. Cowan (2001) demonstrated during immediate recall tasks that familiar words were better recalled than non-familiar words (i.e., lexical effects), in contrast to Baddeley’s suggestion of a similarity effect. This is due to familiar words being represented in long-term memory. However, the theory posits that the activation of items also influences how well they will be recalled. For instance, Cowan suggests when performing memory tasks items become activated within our primary memory, activated items may then become the focus of attention. The focus of attention refers to items that are currently being attended to and is made possible by executive processes devoting attentional resources to concentrate on the desired items.

A consequence of this assumption is that all activated memories should be remembered. However, the activation of a memory does not necessarily result in that item being readily available for conscious awareness. It is only when the central executive makes items the focus of attention are they able to be recalled and available for conscious awareness (Cowan, 1995, 2001; Cowan, Rouder, Blume, & Saults, 2012; Neath, & Surprenant, 2003). The model proposes that the central executive devotes attentional resources to either processing items internally through long-term memory associations, or by focusing attention
externally by attending to items within the focus of attention. Respectively, long-term memory processes familiar items while the focus of attention processes un-familiar items. While long term memory can only be utilised for familiar items (e.g., items located within long term memory), the central executive has the ability to focus attention on both novel items, and familiar items. This raises further theoretical questions in reference to how many items can be attended to within the focus of attention.

According to Cowan (2001), a maximum of 3-5 chunks of items can be activated within the focus of attention. Chunking occurs through grouping items together by organising them into logical categories (or chunks) through a common characteristic such as contextual similarities or belonging to the same item category (e.g. food, animals, countries etc.; Chen, 2005; Chen, 2009; Cowan, 2001; Miller, 1956). This suggests that within immediate serial recall tasks participants will be able to recall a maximum of four item chunks. Opposing theories stipulate that only one chunk can be readily available in the focus of attention and available for retrieval (Oberauer, 2002).

Cowan’s (1995) theory indicates there are no WM subsystems (e.g., phonological loop visuo-spatial sketch pad) as outlined in Baddeley’s multi-component theory. This suggests that both phonological and visual information are processed and encoded within the focus of attention. This opposes Baddeley’s theory that phonological and visual information can be processed simultaneously with relatively little interference for the retrieval of the other items. Cowan argues that all information is processed within the same system and is subject to attentional demands and voluntary processing of the central executive. The strength of item recall depends on how salient the information is activated within long-term memory or which items are the current focus of attention. Cowan’s model suggests that WM is the activation of long-term memory and that the mode of information does not impact on recall, refuting Baddeley’s concept of dual task modality.
The model suggests that the limits of WM do not depend on the type of stimulus but rather on the role of attention and item activation within WM. Cowan’s model is similar to Baddeley’s as rehearsal seems to be a key component of item retrieval to keep items activated. For example, Cowan (2001) showed that the longer attention is captured by a secondary task, the greater the decay in memory (Cowan, 2001). That is, if a secondary task captures attention, it will prevent resources focusing on the processing and maintenance of to-be-remembered items. The longer resources are diverted from keeping items within the focus of attention the more likely there will be a weakening memory trace and increased forgetting. On the other hand, Baddeley maintains that as long as items are continually refreshed through sub-vocal rehearsal, they will be remembered.

The embedded process theory has helped define, contribute, and advance subsequent research into identifying that WM may have a general attention capacity as opposed to a domain specific attention capacity. To put it simply, when attention is divided between two tasks, resources will be diminished regardless of the type of information being processed (e.g., phonological or visuo-spatial). While Baddeley indicates, dual tasks that are processed in separate sub-systems remain relatively unaffected. Cowan’s (2001) model suggests attention is a limited central resource and when two demanding tasks are completed simultaneously attentional resources become scarce and performance will suffer regardless of the modality of the information. The longer that attention can focus on activating items the better recall of that item. If attention is switched away from maintaining items in the focus of attention (for example, towards a demanding secondary task) that memory is subjected to decay. The longer the attention is switched away from the focus of attention the greater the decay. Additionally, Cowan (2010) did find that there was more interference for tasks of the same modality. However, the interference was due to the inability to encode the secondary memory items while maintaining the first set, not due to the modality. In contrast to Baddeley, Cowan
provided evidence for a central storage system that processes both verbal and spatial
information.

Cowan’s notion of WM as activated long term memory contributed to the debate on
how memory becomes long term memory, the saliency of activated long term memory, and
does the way we process an item influence how well it will be remembered? Researchers have
attempted to answer these questions for many decades resulting in research that both opposes
and supports these concepts.

1.1.3 Executive attention theory and controlled attention

The executive attention theory and controlled attention model (Engle & Kane, 2004) is
not another attempt to critique Baddeley’s model but rather an explanation to show how
attention is the mechanism governing WM capacity. Engle, Kane, and Tuholski (1999)
introduced the executive attention model of WM and proposed a general attention capacity
rather than domain specific limitations. The main focus of the model is the ability to control
attentional resources during dual tasks. For example, when performing a concurrent distractor
task during a WM task, the ability to control attention can determine WM performance. If
attention cannot be controlled efficiently the distractor task will reduce the available attention
that can be used to process, maintain, and recall information within WM. Conversely, the
ability to efficiently control attention allows the suppression or blocking of the distractor task.
This results in more efficient WM processes and an increase in recall. This theory also
touches on aspects of Cowan’s (2001) model suggesting WM capacity is also responsible for
our ability to control and activate memory. For example, deciding which items should be the
focus of attention and the ability to maintain focus when distractions occur.

What separates the controlled attention model from other general attention models
such as Cowan’s, is that it explains the use of executive attention in the context of Baddeley’s
model. Engle (2002); and Kane, Bleckley, Conway, and Engle (2001) acknowledge that WM
has temporary memory stores (e.g., phonological loop and visuo-spatial sketch pad) that utilise separate processing mechanisms depending on the mode of the information being processed. Rather than suggesting each subsystem has domain specific limitations they have provided evidence for a central attentional resource that governs the activation of information that is within the subsystems at any given time. Kane, Blackley, Conway, and Engle, (2001) also found that when participants were required to divide attention between multiple tasks, proactive interference became more prevalent. When attention was needed to perform two tasks, they were less effective at maintaining attentional control and became susceptible to interference. However, under single task conditions they were effective at maintaining attentional control and inhibiting distractors. When completing dual tasks, the limited attentional resources must be divided and allocated to both tasks, either equally or disproportionately depending on the differing difficulty or complexity of the concurrent task. This provides evidence for a general attention limit of working memory.

Baddeley provided evidence to show that dual tasks can be processed relatively well and performance remains unaffected when separate subsystems are activated. Conversely, the executive attention model suggests a central attention limit exists. This indicates that if two complex tasks are processed simultaneously attention will need to be split and could reduce the efficiency to process information adequately. This model contrasts Baddeley’s suggestion of domain specific limitations, suggesting that when a central limited pool of resources is exhausted, there will be a decrease in performance across all working memory domains (e.g., phonological loop, visual, and spatial). This opposes Baddeley’s suggestion that dual task modality can remain relatively unaffected when information is processed in different subsystems.

Kane, Bleckley, Conway, and Engle, (2001) also found that when participants were required to divide attention between multiple tasks, proactive interference became more prevalent. When attention was needed to perform two tasks, they were less effective at
maintaining attentional control and became susceptible to interference. However, under single task conditions they were effective at maintaining attentional control and inhibiting distractors. When completing dual tasks, the limited attentional resources must be divided and allocated to both tasks, either equally or disproportionately depending on the differing difficulty or complexity of the concurrent task. This provides evidence for a general attention limit of working memory.

The executive attention theory suggests attention is just as important in maintaining a single item in WM as processing multiple items. If attention is not controlled, information will not be maintained. This is opposed to Cowan’s suggestion that WM has a limit of 3-5 items. This implies WM capacity is not limited by the number of items that can be maintained but by the ability to control attentional resources. For example, high WM capacity individuals are able to control attention more efficiently than low WM capacity individuals. The individual differences in how many items can be retained is more of a reflection of their ability to control attention rather than the maximum capacity of WM. Additionally, they outline that attention is essential to maintain current items as the focus while being able to inhibit distractions and maintain attentional focus on the goal. For example, participants who have relatively lower WM spans are more vulnerable to distractions. This has been shown multiple times, where participants with low WM spans recall fewer items because they are more susceptible to distractions from irrelevant items, or previously presented items (e.g., Conway & Engle, 1994; Engle, Kane, & Tuholski, 1999; Rosen & Engle, 1998). A practical implication of this would be trying to have a conversation in a crowded room. Your ability to maintain a conversation efficiently, is dependent on how well you can inhibit distractions from extraneous noise in the room that are not relevant to your conversation.

Engle, Kane, and Tuholski (1999) provide evidence for a general attention limit but maintain that information can be processed in separate subsystems. This implies that performance deteriorates when attention must be divided between two demanding cognitive
tasks. This suggestion is also consistent with neurological explanations of WM (e.g., Postle, 2006), whereby WM is a result of pre-frontal activation of neurological regions responsible for processing verbal, visual, and spatial information.

### 1.1.4 Working memory as an emergent property

As noted previously, the proposal of separate subsystems has been shown to be neurologically improbable. To rectify the problems associated with the continual fractioning of the multi-component model as proposed by Baddeley and Logie (1999; Baddeley, 2000), alternative models of WM have been developed to show how attention is utilised at a neurological level to explain the mechanisms of WM (Postle, 2006).

The standard model of WM (Baddeley & Hitch, 1974; Goldman-Rakic, 1987) proposes that all WM processes are subject to processing and manipulation in the pre-frontal cortex (PFC; Postle, 2006). For example, the visuo-spatial sketch pad, phonological loop, episodic buffer, and central executive are all mechanisms controlled by the PFC, and processing and storage occurs within it. However, recent evidence has begun to point to alternative explanations and the implausibility of separate sub-systems within the PFC to process verbal, visual, and spatial information. Instead, recent models (e.g. Postle, 2006) have begun to theorise that WM is the product of attention being directed to pre-established neurological regions to process verbal, visual, and spatial information. The model will be discussed below, but for a more in depth discussion of the emergent process model see Postle (2006, p 10-17)

When processing stimuli for the purpose of a WM task, Postle (2006) proposes that the stimulus is not processed within the PFC. But attentional resources that are governed by the PFC for WM purposes are allocated to the neurological area responsible for processing that specific type of sensory input. For example, if required to remember a specific spatial
location, attention is allocated to the neurological regions responsible for processing the perception of location (i.e., parietal cortex; Postle 2006). What these principles propose is that the PFC is not involved in or capable of memory storage. Its primary purpose is to allocate attention to other neurological regions to aid in the temporary activation and retention of to-be-remembered stimuli. Postle’s (2006) model incorporates two core assumptions that contribute to the conceptualisation of the model from both a theoretical and neurobiological perspective. These assumptions allow a robust evaluation of current literature and a new direction for the development of the role of attention in WM.

The first assumption is similar to that proposed by Cowan (1995), that WM is the activation of representations in long-term memory. In order to remember information in WM, attention must be allocated to the neural regions associated with processing that type of sensory input even when WM is not engaged. For example, motor movements, speech recognition, verbal fluency, spelling, spatial location, and directions. If executive attention is not directed towards the neurological areas where the sensory information is processed, that sensory input will fall outside of the focus of attention and will not be maintained.

The second assumption is the role of multiple encoding, which suggests that when processing a stimulus, we employ as much mental effort as is required to process the stimulus (Postle, 2006). Multiple encoding is the ability to process an item within multiple codes to ensure the stimulus is given the best possible opportunity to be remembered. Multiple encoding also allows executive control for sequential ordering (i.e., serial position). Further to this, Postle suggests that multiple encoding does not just process the stimulus, but also the context in which the stimulus was presented all which may contribute to enriching the memory and it becoming more salient. Postle (2006) uses the example of remembering a phone number. When we are required to remember a mobile phone number, it is not just the digits that are processed within WM. We also process information on who was speaking, the volume, and the tone of the sensory input (i.e., multiple encoding). During this process, long
term memory may also be activated and associations to similar numbers may be made. For example, in Australia all ten digit mobile numbers start with ‘04’. When hearing a new mobile number, the first two digits are easily retrieved from long-term memory. This allows more attention to be focussed on processing the remaining eight digits without allocating resources to processing the first digits as that information is readily accessible from long term memory. Taken together, multiple encoding makes some large assumptions and allocates a lot of responsibility for processing, maintaining, and activating multiple neurological areas to process stimuli and contextual information. The emergent process model of WM has been an influential model of WM in recent years and has spurred on neurological and theoretical research (e.g., Chein & Fiez, 2010; Macdonald, 2015; Maidment, Macken, & Jones, 2013; Maidment & Macken, 2012; Nee & Jonides, 2011; Verwey, Shea, & Wright, 2014).

Postle’s model is relatively new and has had some criticisms (e.g. Auksztulewicz, Spitzer & Blankenburg, 2012; Bancroft, Hockley, & Servos, 2014; Christophel, Hebart, & Haynes, 2012; Spitzer & Blankenburg, 2011; Spitzer, Gloel, Schmidt, & Lankenburg, 2013; Spitzer, Wacker, & Blankenburg, 2010). For example, a major criticism of the emergent property model is the proposal that the PFC does not engage in memory storage. However, despite recent criticisms, the emergent property model of WM has had an influence on other recent models of WM and the importance of the allocation of attention for the processing of multi-coded stimuli within WM.
1.1.5 **Time-based resource-sharing model of working memory**

The TBRS model of WM (Barrouillet & Camos, 2007; Barrouillet, Bernardin, & Camos, 2004) gives insight into how resources are shared between WM and concurrent tasks. This model is concerned with the time related decay of information when attention (the resource) is diverted away from the original focus of attention. The longer attention is captured elsewhere, the poorer the performance on the original process or task. The model assumes that both the processing and maintenance of information utilises a limited attentional resource, and that attention is rapidly switched between them. Additionally, it is assumed that a central bottleneck exists which only allows one cognitive process to occur at a time. When performing multiple cognitive tasks, the sharing/switching of that resource is automatic. If attention is diverted away from the processing and maintenance of the memory item, then it is subject to decay. This increases the risk of items being forgotten and only by focussing attention back to processing and maintenance can the item be retrieved (Cowan, 1995, 2001, 2010). The longer that the item is not activated the more decay it is subject to and the harder it will be to re-activate when attention can be diverted back to maintenance and processing (Cowan, 1995, Oberauer, 2002). Therefore, it is suggested that any process that captures attention can hinder the processing, maintenance, and retrieval of to-be-remembered items (Barrouillet & Camos, 2007). In the context of this thesis, I argue that the processing required to produce handwriting will capture attention and prevent resources switching back to working memory.

The importance of the TBRS model is that it implies that WM performance is dependent on how long attention can be devoted to processing and maintenance. When attention is switched away from WM, the memory items are subjected to periods of decay. For instance, a secondary task that captures attention for a long period will prevent resources switching back to processing and maintenance. Conversely, a secondary task that captures
attention for a relatively shorter period will result in more efficient switching of resources. Another consideration of this model is that the capturing of attention is not solely determined by task complexity, instead it suggests that tasks that constantly capture attention for long periods prevent the switching of resources back to processing and maintenance.

The model proposed by Barrouillet and Camos (2007) consists of four main assumptions. Firstly, there are limited resources available to share between processing and maintenance. When performing WM tasks, attention is required for all aspects of processing and maintenance. To maintain efficiency on all the different WM mechanisms, attention must be switched rapidly between them to maximise performance across all the different components. Therefore, attention is needed to actively maintain memory traces. When attention is diverted, items are no longer the focus of attention and are subject to decay. However, if resources are sufficient, items can remain readily available (Cowan, 1995, 2001).

The second assumption is set within the framework of Cowan’s (1995) model of WM. This posits that there is strong emphasis on the focus of attention, and that items need to be actively maintained to be remembered. A consequence of attention being diverted from the memory item results in time-related decay and limited ability to retrieve that item from memory. Specifically, this occurs when attention is switched from maintenance to processing (i.e., encoding) - as soon as attention is diverted, memory decay occurs. This requires constant switching of attention to ensure the items are not forgotten but actively maintained within the focus of attention.

The third assumption is that any process that requires attention can result in interference/decay and hinders the ability maintain and process items within the focus of attention. Specifically, Barrouillet and Camos (2007) suggest that a bottleneck exists, whereby only one process can be occurring at a time. This limits the ability to recall memories, from this they speculated that if attention is captured during the recall phase that performance will decrease dramatically as items cannot be maintained efficiently. Barrouillet and Camos
(2007) suggest that any secondary task that captures attention will have a detrimental effect on processing, maintenance, and later retrieval. They specifically note a study by Rohrer and Pashler (2003) who concluded that even an unrelated secondary task that utilises the central pool of resources will result in the interference and reduction in the available resources for processing and maintaining relevant items in WM.

The fourth assumption suggests that only one process can occur at a time and that the sharing of attention occurs over time and must be switched between tasks. The model suggests that to adjust to the demands of complex dual tasks, that attention must be controlled and switched constantly between the dual task to maintain and process each of them efficiently. The theory proposes that attention allocation does not occur concurrently but over time. The model is a comprehensive framework of how attention is shared between the maintenance and processing of WM. The sharing of attentional resources is a key component of the model and is essential to explain how attention is shared during dual-task. One of the proposals of the model is that there is a limited pool of resources that is shared between the maintenance and processing of WM, secondly it is proposed that any process or task that demands attention would result in a decrease in the availability of resources.

The WM literature I have covered thus far is an overview of some of the key models that are pertinent to this thesis. The role of attention in WM is apparent, and my thesis is concerned with how attention is shared between multiple tasks. Additionally, I aim to uncover whether handwriting captures resources while performing a concurrent WM task, and what aspects of handwriting contribute to this. For this purpose, the TBRS model will be the core model I will be testing and interpreting the results within. While at times, there is reason to include aspects of Baddeley’s phonological loop and Cowan’s focus of attention, the model that is of most interest and pertinence to the thesis is Barrouillet and Camos’ (2007) TBRS model.
1.2 Models of Handwriting

1.2.1 Kellogg’s (1996) model of working memory in writing

Kellogg (1996) developed a model to explain how writing and WM interact and outlined how WM was utilised during the writing process. Kellogg’s model argues that writing utilises the phonological loop for translating words, sentences, and letters as well as for editing purposes; the visuo-spatial sketch pad for motor movement and forming and transcribing letters in the correct size and spatial sequence. The central executive is utilised to provide resources to the phonological loop and visuo-spatial sketch pad when the demands of writing become too great for the subsystems. For a full review of the model’s assumptions see Kellogg (1996). In the context of this literature review I will outline the key components of the model, their purpose and interaction with WM.

The WM in writing model was conceptualised based on the original WM model proposed by Baddeley, before the inception of the episodic buffer. Therefore, some of the mechanisms outlined to be controlled by the central executive may be outdated and in need of a review. The model consists of three systems of writing; formulation, execution, and monitoring. All three components of writing rely on one another as well as WM to ensure the writing task is completed efficiently (see Figure 1.2).

Kellogg (1996) notes that writing has three stages of composition - forming, executing, and monitoring, which are concerned with the planning, execution, and editing of written material. Kellogg (2001) also showed that writing utilises a central pool of resources that is disseminated and controlled by executive functioning (Baddeley, 2000, 2012). This concept has been supported by research indicating that all aspects of the writing process utilise and compete for WM resources (Bourdin & Fayol, 1994, 2002; Brown, Mcdonald, Brown, & Carr, 1988; Graham, Berninger, Abbott, Abbott, & Whitaker, 1997; Kellogg, 1996; McCutchen, 1996). It is also apparent that the different components of writing draw upon the
common pool of resources associated with WM, this has been shown in studies with children (Berninger et al., 1992; Bourdin & Fayol, 1994; Graham, Berninger, Abbott, Abbott, & Whitaker, 1997) and adults (Bourdin & Fayol, 2002; Brown, Mcdonald, Brown, & Carr, 1988). This was demonstrated by Kellogg (2001) by manipulating the demands on the different writing components. By reducing the demand placed on planning, participants’ performance increased on a secondary probe detection task as more resources could be utilised for that task.

If we have a deeper look at Kellogg’s (1996) model of WM in writing, we can begin to disentangle the different components of writing and how WM aids in its production. Throughout the different stages of writing, WM processes are utilised. When preparing to write a specific word (for adults and children), the verbal, visual, and spatial components of WM are activated (Berninger & Richards, 2012; Berninger et al., 1992; Berninger, 1999; Ellis, 1982; Graham, Harris, & Fink, 2000; Kellogg, 1996, 2001; Teulings, 1996; Tse, Thanapalan, & Chan, 2014). During planning, visual and spatial WM is utilised to plan movements. This ensures that the letters are in the correct spatial sequence (Kellogg, 1996; Tse, Thanapalan, & Chan, 2014) and that the spacing between words and the size of the letters is correct (Ellis, 1982; Graham et al., 2000; Teulings, 1996; Tse et al., 2014). In a study by Graham et al., (2000), induced phonological awareness in first-grade students by asking them to identify what letter a word started with (e.g., what letter does “Bin” start with). Their results demonstrated that increasing phonological awareness enhanced handwriting composition and fluency, up to 6 month later. By engaging with long-term memory to draw upon previous knowledge and engaging with the phonetics of the words, verbal WM is utilised to plan the phonetic components of the words (Ellis, 1982; Graham et al., 2000; Tse et al., 2014) and ensure correct spelling.

After the planning stage, written output is executed in conjunction with monitoring/editing (Kellogg, 1996). The written output is guided by visual and spatial WM to
ensure that the movements are legible, while constantly updating, monitoring, and editing to correct changes in movements or verbal inaccuracies in the written output. Meanwhile, the central executive directs resources between all the different mechanisms of writing. More recent evidence by Tse et al.’s (2014) investigate the visual mechanism of child handwriting. Tse et al. (2014) further supported the notion that writing is a complex task that requires an integration of visual, spatial, and verbal WM, as well as motor control and attention to execute proficiently. While it is likely that writing difficulties are more pronounced in children due to the lack of automatization of the required mechanisms. The same mechanisms are also present in adult handwriting, however, these skills become more automatic in adulthood (Tucha & Lange 2005).

The interaction between WM and writing processes is complex and requires the sharing of a limited pool of cognitive resources. The performance of WM tasks and writing tasks is determined by the availability of those cognitive resources and how they are shared. This is to ensure efficient and legible writing while maintaining the active components of WM. When performing a writing task, WM is engaged automatically. This process cannot be inhibited, as it is a necessity to manage the demands of writing.

Figure 1.2 Working memory in writing model adapted from Kellogg (1996, p59) “The resources of working memory used by the formulation, execution, and monitoring system”.

Kellogg’s Model of Working Memory in Writing

Figure 1.2 Working memory in writing model adapted from Kellogg (1996, p59) “The resources of working memory used by the formulation, execution, and monitoring system”.

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While Kellogg’s work is not the first to interpret how cognition is involved in writing, the model is the first comprehensive model to show how the components of WM and the systems of writing (planning, execution, and editing) interact. While the model is dated, there have been recent studies (e.g., Olive, 2004) outlining the role of WM in writing.

Olive (2004) conducted a review of the literature surrounding the topic of working memory’s role in writing. Specifically, Olive (2004) focussed on how dual task techniques, - the requirement to simultaneously complete two tasks to strain the limited cognitive resources - can be used to assess how working memory resources are utilised during writing.

The robustness of Kellogg’s model of working memory and the flexibility of the theory to adapt to the role of working memory in writing is also discussed. For example, Olive (2004) identifies that (1) writing relies on working memory processes to produce written text, namely, the role of short-term storage of visual, spatial, and verbal information within working memory to produce written text; and (2) Writing requires multiple cognitive processes that rely on working memory, and suggests that by utilising dual-task techniques, the attentional limitations and requirements of writing can be investigated. There are significant limitations in our understanding of how the cognitive mechanisms of writing contribute to producing written text. By using dual-task techniques we can effectively measure the individual impact of the verbal components of writing, the visual and spatial components of writing, and the kinematic movements needed to produce writing (i.e., handwriting).
1.2.2 Alternative Models of Handwriting

Peverly (2006) conducted a literature review on the speed of handwriting in adults. Peverly reviews cognitive models of writing and emphasises the importance of planning, translating, and revising during the writing processes. Peverly stresses that more importance should be rendered to investigating the transcription phase of handwriting, which includes the automaticity of motor-movements and spelling. Peverly outlines the importance of WM in handwriting and identifies that even highly fluent writers rely on WM to produce fluent and legible handwriting. It is concluded that handwriting speed is essential to enable WM to be utilised for higher order cognitive processes. For example, when handwriting becomes fluent (speed of transcription increases), WM resources can be utilised for higher order cognitive processes needed to encode, maintain, and integrate information in WM. The cognitive processes outlined in Peverly’s (2006) study are consistent with those outlined in Kellogg’s Model of WM in writing. This further stresses the importance of working memory in handwriting and the importance of kinematic measures, such as handwriting speed.

Multiple studies have investigated the kinematic requirements needed to draw and write (Plamondon, & Maarse, 1989; Van Galen, 1991) and have often been used to capture cognitive load (e.g., Luria & Rosenblum, 2012; Werner & Rosenblum, 2006; Yu, Epps, & Chen, 2011). Plamondon, & Maarse (1989), simulated multiple theoretical models of handwriting motor control. Their findings showed that handwriting motor control is velocity-controlled. This suggests that kinematic measures that are derived from velocity are predicted to best resemble natural handwriting. Therefore, measures such as duration, acceleration, velocity, and jerk are measures associated with handwriting motor control. The notion that handwriting is a cognitively complex skill due to the kinematic nature of the task has also been addressed.

Van Galen (1991) reviewed the handwriting literature to develop a multi-component psychomotor theory of handwriting. The studies evaluated assessed psychomotor movement as
individual stroke formations, and assessed the size, duration, speed, velocity, and writing fluency, which have been established as cognitive-motor demands associated with handwriting. Van Galen proposes as hierarchical handwriting model, whereby the handwriting production of a single stroke is dependent on the generation of ideas from episodic memory to conceptualise the semantics and verbal lexicons. Short-term memory is then engaged to construct phrases, which requires retrieving information on how to spell words. Finally, the motor systems are activated to convert phonemes to graphemes, and evaluate the size and movements needed to produce each individual stroke. For an in-depth review and visualisation of this model refer to Van Galen (1991, pp 183).

Taken together, various theoretical models of handwriting indicate that there are multiple stages required to produce written output. This identifies the complex nature of handwriting, and the need for multiple cognitive process to occur sequentially, and simultaneously to ensure the written output is legible. The evidence emphasises the importance to assess the kinematic components of handwriting and to further investigate the interaction between memory and handwriting kinematics. The above models indicate that handwriting is complex, multi-faceted, and relies on multiple cognitive systems including short-term memory and WM. Therefore, it is of importance to evaluate how the cognitive complexity of handwriting movements might impact on WM performance.

1.2.2 Handwriting and Working Memory

Handwriting is a complex skill that requires an integration of visual, spatial, phonological, motor control, attention, and memory processes to execute proficiently (Tse, Thanapalan, & Chan, 2014). Of these, attention is crucial for ensuring all these processes occur, for the handwriting to be legible and fluent when the word is produced. WM is also an important factor in handwriting tasks (Kellogg, 2004), specifically visual and spatial processes are important when transcribing or creating letters, words, and sentences. The
creation of a visual representation of the words in WM guides the movements needed to produce handwriting (Hagura et al., 2007; Tse et al., 2014). In addition to this, the writing process draws upon phonological and long term memory processes when processing the sounds, syllables, meaning, and spelling of words. This information must be temporarily stored in the phonological loop before being transcribed externally. These processes are complex and require large amounts of attention to perform the tasks simultaneously. The role of complexity in handwriting seems to mediate the attentional load to complete the task efficiently (Torrance, 2008; Tse et al., 2014; Tucha et al., 2006).

The notion of task complexity in determining whether WM storage occurs in the PFC has recently been investigated (Bancroft, Hockley, & Servos, 2014). Research has indicated the more cognitively complex a task is (such as writing) the greater the demand placed on WM (Baddeley, 2003; Kellogg, 1996, as cited in Olive, 2004; Kellogg 2001; McCutchen, 1996, 2000; Torrance, 2008; Tse et al., 2014; Tucha et al., 2006). Bancroft, Hockley, and Servos (2014) defined the term complexity, within the confines of the to-be-remembered stimulus and the task requirements. The complexity of a stimuli might be defined by the number of dimensions required to process it within WM. For example, a stimulus with a single dimension might include tasks that require participants to decide if two images belong to the same category. This response does not require the participant to remember all the peripheral information associated with the stimulus (which could be quite complex) but only the category (which is one dimensional). A multi-dimensional stimulus will result in greater cognitive complexity and could result in a reduction in the ability to remember stimuli that is multi-dimensional. Bancroft et al. (2014) determined that at a neurological level the complexity and dimensionality of a stimulus influenced how information was processed and how well it would be remembered.

It appears that WM performance is reduced when an individual engages (children or adults) in a writing task (Bourdin & Fayol, 1994; Klein & Boals, 2001 McCutchen, 2000;
McCutchen et al., 1994; Olive, 2004; Peverly, 2006). Our ability to store information in WM seems to be impaired when an individual is asked to write down large amounts of information while listening to words, sentences, paragraphs, or lectures (Peverly, 2006). Peverly (2006) suggests this may be due to the cognitive complexity of the writing process, as it requires a high level of cognitive effort, therefore inhibiting WM processes. However, these studies have been concerned with producing large passages of text (e.g., essays). They have not identified how the lower levels demands of writing, namely, handwriting and spelling (Janssen, Braaksma, & Rijlaarsdam, 2010; Swanson & Berninger, 1996; Vanderberg & Swanson, 2006) affect WM performance. When I refer to handwriting, I am concerned with the motor requirements needed to produce letters and words, as well as ensuring the correct spatial sequence of letters (Berninger & Graham, 1998). Handwriting is also concerned with the verbal requirements needed to spell words and form legible sequences of letters. As noted above, writing has been investigated in regard to how it overloads and relies on WM, typically for generating large passages of text. However, there is little research on how the lower level demands of handwriting contribute to a reduction in WM performance.

The higher level cognitive processes involved in writing seem to place extra strain on WM, inhibiting our ability to store information in short term memory (McCutchen, 2000). However, while writing appears to impair an individual’s ability to store information in WM, the fluency (as defined by the speed of word production), of an individual’s writing also appears to play a role in determining their capacity to recall information (Haenggi & Perfetti, 1992; McCutchen et.al, 1994; Olive, 2004; Peverly, 2006; Peverly, et al., 2007). Olive (2004) evaluated the fluency of participants’ writing in a separate task and correlated it with how well they recalled information. The participants with more fluent writing were able to recall more information from WM then those with slower handwriting. Olive (2004) argues that the speed of an individual’s writing will impact on their recall capacity, this suggests writing places a higher demand on cognitive processes, limiting WM capacity (Peverly, 2006).
It is plausible that individuals with more fluent writing place a smaller demand on their cognitive processes, therefore placing less strain on WM than those with slower handwriting (Bourdin & Fayol, 1994; Klein & Boals, 2001). This enables WM to work at a higher level of processing than those with less fluent writing, allowing WM to store and process more information (Benton, Kraft, Glover, & Plake, 1984; McCutchen, 2000; McCutchen et al., 1994; Peverly, 2006; Peverly, et al., 2007). In McCutchen’s (2000) review of the literature, the main findings were that WM is inhibited when more cognitive resources are being devoted to higher order processes such as writing. Additionally, the reviewed literature suggested those with relatively dysfluent writing skills (e.g., in terms of language generation) had deficits in short-term memory capacity. Conversely, fluent writers had more automatic cognitive process, which allowed them to utilise long-term memory to draw upon previous knowledge. For example, skilled writers can fluently process, generate, and transcribe text, by utilising knowledge stores on the topic, produce automated motor movements. In comparison, novice writers generally have dysfluent text generation and rely on a limited resource base (i.e., short-term memory) to produce text. McCutchen also demonstrated that when an individual is focused on memory storage, extra cognitive effort is devoted to memory processes inhibiting the fluency of the writing process.

Baddeley’s (2003) model of WM suggests that limited processing capabilities of the central executive and its inability to devote processes to the phonological store, prevent the rehearsal of information. In relation to writing, Kellogg (1996; Kellogg, 2001; Olive, 2004) suggests the limits of WM during writing are due to the higher cognitive processes and demand placed on the central executive inhibiting its ability to devote processes to the phonological store. Both McCutchen (1996, 2000) and Kellogg, (2001) address the theory that higher cognitive processes increase the demand on WM suggesting the more cognitively complex a task is the greater the resulting deficit in WMC. Their studies specifically indicate both reading and writing place higher demands on WM. This may be attributed to the central
executive’s limited capacity and inability to devote processes to the phonological loop (Kellogg, 1996, Olive, 2004) or as proposed by McCutchen, trade-offs may exist between storage of information and the fluency of reading or writing. Their theories suggest that tasks with low cognitive complexity would result in increased storage ability and processing fluency. Taken together, these studies suggest that the cognitive complexity of writing inhibits our ability to temporarily store information in WM.

Tasks such as writing that require fine motor movements tend to increase the cognitive and attentional load within individuals. However, it is unclear how much of the cognitive demand is due to the phonological processes and engagement with long term memory (spelling, comprehension, grammar) or the fine motor movements required to perform the writing tasks. Previous studies (e.g., Galen, 2005; Graham, Berninger, Abbott, Abbott, & Whitaker, 1997; McCutchen, 2000; Peverly, 2006; Peverly et al., 2007; Ransdell, Levy, & Kellogg, 2002) have assessed the impact of fluency as a measure of speed and outlined that the motor movements may be having an impact on WM processes. For instance, during memory tasks the increased attentional demand needed for the movements, draws attention away from the memory task and results in poorer retrieval of information. The increased cognitive demand to perform movements that are normally automatic may contribute to a reduction in WM performance.

It is worth mentioning that research has shown that in general, note-taking is correlated well with later recall of information. For example, Connelly, Dockrell, and Barnett, (2005) and Peverly et al. (2007) investigated handwriting fluency in undergraduate students and found that note-taking and exam marks are correlated well with one another. However, their research has focussed more on comprehension, which is concerned with long term memory and the ability to read back over notes at later stages, which tends to enhance learning. In this literature review, I have focussed on the immediate effects on recall while writing. The literature covered is better suited to circumstances where individuals are writing
down information while another is talking, and then being asked to recall information. For example, if you are in a board meeting and taking notes while a colleague is presenting information, the cognitive complexity of writing down words may interfere with your ability to adequately process incoming information. When asked a question about what has just been said, you may not be able to accurately answer as some information has not been processed efficiently as it was interfered with by the writing process.

1.3 Handwriting, Working Memory, and the Time-Based Resource-Sharing Model

There are significant cognitive demands associated with producing written material (Kellogg, 1987, 1988, 1999, 2001) and WM is important for this process (Kellogg, 1996; McCutchen, 1996). As noted at the beginning of this review, WM is a limited capacity cognitive system with the purpose of temporarily manipulating, processing, maintaining, and retrieving task oriented information (Baddeley, 1976, 2000, 2012; Baddeley & Hitch, 1974; Barrouillet & Camos, 2007; Cowan, Fristoe, Elliott, Brunner, & Saults, 2006; Cowan, 2001; Gathercole, 2008; Logie, 2011; Unsworth, Heitz, Schrock, & Engle, 2005).

Bourdin and Fayol (1994) investigated how WM performance is hindered by a handwriting task in undergraduate students and children. Specifically, they required participants to recall information in a written format or in an oral format. Their results indicated a significant modality by age interaction, with no difference in recall occurring between the written and spoken formats for adults. Despite this, they did identify that when adults abandoned their over learnt handwriting skills by writing in cursive upper-case letters that a reduction in serial recall occurred compared to responding verbally (Bourdin & Fayol, 1994; McCutchen, 1995). Their results were explained by the notion that WM and handwriting draw upon the same limited pool of resources. They suggested that when resources were devoted to one aspect of the task that this would limit the availability of resources that could be devoted to other components of the task. The sharing of a limited pool
of resources resulted in a reduction WM performance when a handwriting task was performed concurrently during retrieval. However, further investigation is needed to understand how resources are shared between handwriting and WM during encoding and maintenance in adults.

The TBRS model (Barrouillet & Camos, 2007; Barrouillet, Bernardin, & Camos, 2004) gives insight into how resources are shared between WM and concurrent tasks. This model is concerned with the time related decay of information when attention (the resource) is diverted away from the original focus of attention. The longer attention is captured elsewhere, the poorer the performance on the original process or task. The model assumes that the processing and maintenance of relevant information utilises a limited attentional resource, and that attention is rapidly switched between them. Additionally, it is assumed that a central bottleneck exists which only allows one cognitive process to occur at a time. When performing multiple cognitive tasks, the sharing/switching of that resource is automatic. If attention is diverted from the maintenance and processing of the memory item, then it is subject to decay. This increases the risk of items being forgotten and only by focussing attention back to processing and maintenance can the item be retrieved (Cowan, 1995, 2001, 2010). Therefore, it is suggested that any process that captures attention (such as handwriting) hinders the processing, maintenance, and retrieval of to-be-remembered items (Barrouillet & Camos, 2007).

Within the framework of handwriting and the TBRS model, it is plausible that performing a concurrent handwriting task while trying to process and maintain items within WM would capture attention and limit the availability of resources to switch back to process, maintain, and retrieve relevant items. Based on the findings from Kellogg’s (1996) model of WM in writing and recent work by Tse, Thanapalan, and Chan (2014), it appears that handwriting requires WM processing, and places significant demands on attention, limiting the recall of relevant information (Bourdin & Fayol, 1994, 2002; Tindle & Longstaff, 2015).
It is also well established that attention is needed to complete the verbal and spatial components of handwriting. However, it has not been established which component of the handwriting process is responsible for the decrease in WM performance. In other words, if there is a reduction in immediate verbal serial recall, is it due to the complex motor task of handwriting, or due to the verbal component of handwriting, or both?

Previous literature has only investigated the holistic aspects of handwriting, and only its detrimental effect when handwriting is conducted during retrieval (Bourdin & Fayol, 1994, 2002). However, we do not have a grasp on how the different components of handwriting are interfering with WM processes. The current thesis investigates if there will be a decrease in verbal serial recall performance when a handwriting task is performed during the processing and maintenance stage of WM while listening to the words to be recalled. The handwriting task that participants complete will require them to listen to words and write them down verbatim as they are hearing them.

1.4 Conclusion

Throughout the review, I have outlined that tasks requiring fine motor movements such as handwriting require significant cognitive resources to complete the task. This suggests attention is essential in performing cognitive tasks and that those resources are limited. The literature alludes to handwriting as a cognitively demanding – ‘cognitively demanding’ refers to tasks that require or utilise the limited capacity of working memory, tasks that require more resources are considered to be relatively more cognitively demanding (Holmes & Gathercole, 2013; Kieft, Rehearsal, Galbraith, & van den Bergh, 2007; Peverly et al., 2013; Swanson & Berninger, 1996). Therefore, it is suggested that handwriting captures attention and requires WM to process the verbal and spatial components needed to handwrite. The increased cognitive demand required to handwrite might be contributing to a poor WM performance.
Within this thesis, I aim to further explore the relationship between WM and handwriting. Writing, to some extent overloads our ability to immediately retrieve information. However, what has not been identified is how or what components of the handwriting task deteriorate or interfere with WM. To be specific, I aim to uniquely identify if the reduction in WM performance while handwriting can be attributed to verbal aspects and/or the motor aspects of the task. The first step will attempt to establish if there is an effect of concurrent handwriting on WM performance, during encoding and maintenance. Secondly, to pull apart the different components of the handwriting process to identify which aspect of writing contributes to the interference. Thirdly, to investigate if there is a relationship between handwriting kinematic measures of fluency and working memory performance. Fourthly, an investigation into what cognitive mechanism may be contributing to the reduction of WM performance while handwriting will be conducted. Lastly, I will identify if movements alone reduce WM performance, and if different types of movement affect WM differently. In Table 1 an overview of the aims, independent and dependent variables, hypotheses, and key findings for each experimental chapter within the thesis is presented. Before I investigate these concepts, the following chapter will outline some of the key methodologies employed to test verbal WM and handwriting.
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
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<td>3</td>
<td>To identify if handwriting reduces verbal serial recall compared to listening and reading.</td>
<td>1. Secondary tasks: Handwriting, reading, listening. 2. Serial position (1-6)</td>
<td>1. Proportion of words recalled 2. Order errors</td>
<td>It is hypothesized that serial recall will differ between all three conditions, with recall being best in the listening condition, moderate in the reading condition and poorest in the handwriting condition.</td>
<td>Handwriting overloads WM more than reading and listening, leading to worse recall of concurrently presented words. This indicates that handwriting is more cognitively complex and places a greater strain on WM processes than reading and listening.</td>
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<td>4</td>
<td>To identify if handwriting captures attention for significant periods, resulting in a decline in working memory performance.</td>
<td>1. Secondary tasks: Handwriting, pseudohandwriting, handwriting, and listening. 2. Serial position (1-6)</td>
<td>1. Proportion of words recalled 2. Order errors 3. Handwriting Kinematics</td>
<td>It is hypothesized that recall will be significantly different between all three conditions. With recall being the best in the listening condition, moderate in the pseudohandwriting condition, and poorest in the handwriting condition.</td>
<td>Handwriting movements capture attention for significant periods, with little diminution in recall due to the verbal components of handwriting.</td>
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<td>5</td>
<td>To identify whether the movements produced during handwriting contribute to working memory interference.</td>
<td>1. Serial position (1-6) 2. Recall vs No Recall</td>
<td>1. Proportion of words recalled 2. Order errors 3. Handwriting Kinematics</td>
<td>1. There will be a positive relationship between handwriting kinematics and verbal serial recall. 2. Handwriting fluency measures will be worse when concurrently completing a verbal serial recall task compared to just handwriting - without needing to recall.</td>
<td>1. There is no significant relationship between handwriting kinematics and verbal serial recall. 2. There is no difference in handwriting fluency measures when concurrently performing and verbal serial recall task compared to handwriting without the need to recall.</td>
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<td>6</td>
<td>To identify if an attention-demanding secondary task that does not rely on WM will contribute to a reduction in verbal serial recall and handwriting fluency.</td>
<td>1. Secondary tasks: No tapping (Pseudohandwriting), single tapping, and double tapping. 2. Serial Position (1-6)</td>
<td>1. Proportion of words recalled 2. Order errors 3. Handwriting Kinematics 4. Tapping speed</td>
<td>1. Recall performance will be best in the pseudo-handwriting condition, moderate in the single finger tapping condition, and poorest in the double tapping condition. 2. Handwriting fluency will be best in the pseudo-handwriting condition, moderate in the single finger tapping condition, and poorest in the double tapping condition.</td>
<td>1. Recall performance was significant worse for the continuous condition because attention was captured for a longer period relative to the discrete condition. 2. Fine motor movements reduce working memory performance. However, it is not merely performing a movement task, but the type of movement and pattern of emotional demands that is important in determining how resources are diverted.</td>
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<td>7</td>
<td>To identify if performing fine motor movements which are unrelated to handwriting simultaneously while reading to words will result in an interference of verbal WM performance.</td>
<td>1. Secondary tasks: Listening, listening with discrete movements, and listening with continuous movements 2. Serial Position (1-6)</td>
<td>1. Proportion of words recalled 2. Order errors 3. Handwriting Kinematics</td>
<td>1. Recall performance will be best in the Listening condition, moderate in the discrete movement condition, and poorest in the discrete movement condition. 2. Comparisons between the kinematics (speed, size, duration, normalized jerk, number of strokes, and movement pauses) will also be made to help explain any differences that may occur between the conditions.</td>
<td>Provided evidence that patterns of serial recall can be attributed to processes related to the proportion of time words at each serial position decay, are rehearsed, maintained, and encoded.</td>
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Chapter 2 – Methods
In order to investigate if handwriting reduces WM performance when completed concurrently with other tasks, a survey of the methodology used to test verbal WM and handwriting is reviewed in this chapter. As I am only focussing on verbal WM, this chapter will only detail the key methodologies used in this research area. For a more in depth review of methodology used to test different mechanisms of WM, see Appendix A. As I am only concerned with the lower level demands of handwriting, the review of handwriting methodology is mainly concerned with the kinematic measurements of handwriting. At the conclusion of the chapter an appropriate methodology to simultaneously test handwriting and WM will be established.

### 2.1 Verbal working memory

The phonological loop (see Literature Review Chapter 1) is involved in processing verbal information and transforming it into a phonological code for rehearsal and retrieval. The phonological loop has been the focus of research for many decades and many methodologies have been employed to test this construct. Typically, phonological experiments use words, numbers, or sentences as the stimuli where the dependent variable relates to the participant’s ability to retrieve the relevant information.

Verbal WM has been investigated by means of manipulating phonologically coded information or investigating how non-phonological information is converted to a phonological code for encoding and retrieval. A majority of studies have investigated the phonological loop by using word lists (e.g., Acheson, MacDonald, & Postle, 2011; Acheson, Postle, & MacDonald, 2010; Baddeley, & Hitch, 1974; Baddeley & Larsen, 2007; Bublak, Muller, Gron, Reuter, & Von Cramon, 2002; Cowan, Rouder, Blume, & Saults, 2012; Cowan & Saults, 2012; DeDe, Caplan, Kemtes, & Waters, 2004; Jefferies, Lambon Ralph, & Baddeley, 2004; Kellogg, Olive, & Piolat, 2007; Rende, Ramsberger, & Miyake, 2002; Waters, 1996),
Letters (e.g., Baddeley & Larsen, 2007; Barrouillet & Camos, 2001; Bublak et al., 2002; Elsley & Parmentier, 2009), or digit series (e.g., Allen & Hulme, 2006; Altgassen et al., 2007; Barrouillet, Bernardin, & Camos, 2004; Bublak et al., 2002; Chang, Crottaz-Herbette, & Menon, 2007; Greene, 1987; Oberauer, 2002; Savage, Cornish, Manly, & Hollis, 2006; Waters, 1996). Investigating the phonological loop requires experiments that demand the processing of phonological information (e.g., sounds, speech, and written information). In particular, studies have used word lists under different experimental conditions to test aspects of the phonological loop. The following experiments outline a common methodology and various conditions used to investigate the phonological loop.

The most common method of testing phonological processes is through manipulating sentences, word lists, letters, or numbers and investigating the number of items participants are able to recall as well as the number of order errors. Specifically, to gain the most reliable measure of phonological processes and WM, a serial recall task is often adopted to test verbal WM. Employing a serial recall paradigm ensures the participants are encoding, storing, and rehearsing the information while trying to maintain and recall the items in the order they were presented. This is the cognitive manipulation of information. Simply recalling information without maintaining order (i.e. free recall) would best display measures of short-term memory rather than WM, as it does not require the constant maintenance and updating or presentation order, only the item.

Word lists

The most common method is to employ word lists, sentences, or letters to test phonological processes and recall. Experiments often use word lists of 4-12 words (e.g. Baddeley, 2012; Chen & Cowan, 2005, 2009; Cowan, 2001; Martin, Mullennix, Pisoni, & Summers, 1989). However, some controversies arise around the number of words that should
be used for word lists in WM experiments. The main argument is the effect of item length, chunking, and capacity limits of WM.

Cowan (2001) argues, the maximum number of words that can be recalled from any unrelated word list is 3-5 item chunks. A chunk is referred to as the grouping of items through finding a commonality between them and assigning them to an independent category, essentially organising information into logical categories (Chen & Cowan, 2005, 2009; Cowan, 2001; Miller, 1956). This enables the individual to create a single group containing multiple items and can aid in retrieval of information. For example, the items cat, dog, rabbit, car, bus, and train can be chunked into to independent categories; animals (cat, dog, and rabbit) and vehicles (car, bus, and train). Cowan showed that when presented with a list of unrelated items with no chunking, the maximum items able to be recalled is 3-5. Therefore, any item lists containing more than 3-5 items will overload the capacity of WM. Based on Cowan’s study, any word lists created by an experimenter for the purpose of testing WM and overloading its capacity, should ensure there is a minimum of five unrelated words. This can be seen throughout the literature with many studies using word lists of 5 or more items (Allen & Hulme, 2006; Davis, Rame, & Hiscock, 2013; Logie, 2003; Pattamadilok et al., 2010, Saito et.al., 2007; Spurgeon, Ward, & Matthews, 2014). Cowan’s study is one of many outlining the chunking model and the number of items able to be recalled from word lists. Other studies suggest a range from 1-7 items (Miller, 1956), generally most studies indicate an item length of 3-4 chunks per list is the general maximum participant can recall during a WM recall task.

In order to avoid chunking, the word lists used to test phonological processes within WM should be assessed in terms of similarity, word length, and lexical effects (see Chapter 1), while accounting for how many words are within each list, the context, and similarity between items. Further to this, other studies account for other word variables such as familiarity, imagability, lexical effects, meaningfulness, concreteness, and frequency. For example, accounting for familiarity controls for lexical effects. This allows some level of
control over the involvement of long term memory in the activation of processing words. For example, more familiar words will be recalled better, not because they have been processed and maintained in WM efficiently, but because they are activated and retrieved from long term memory.

When choosing words, familiarity should be controlled to limit lexical effects. These variables have been researched considerably and are notable in Paivio et al. (1968) study of concreteness, meaningfulness, and imagery values of 925 nouns, Friendly et al (1982) Toronto word pool, outlining 1080 words on imagery, concreteness, orthography, and grammatical usage. In addition, the Kucera-Francis (1968) word list accounts for word frequency, sampling, and categories. It is typical in many WM studies that utilise word lists to obtain items from the word pools in the above studies. It is a common method for researchers to obtain word lists from the MRC psycholinguistic data base (Coltheart, 1981b), which can be used to control for many of the variables outlined in the above studies and obtain words from the word pools mentioned above.

**Digits**

Traditional models of testing short term memory and WM span have employed the use of digits (Baddeley, 2002). The use of digits in WM experiments seems to be just as consistent as the use of words, as the effect of item length, similarity, and chunking still occur. Experiments using digits as recall items usually employ single digits as an item, for example the digits 1-9 are commonly used, while in some instance experiments employ a 10-digit array by including digits 0-9.

However, research has suggested our ability to recall digits in WM is much more efficient then our ability to recall letters and words (Jefferies, Patterson, Jones, Bateman, & Lambon Ralph, 2004; Wilson & Emmorey, 2006). This suggests it may not be reliable to compare measures of WM based on digit and word lists. The traditional models of digit span
may be an outdated method of testing WM processes. Developments in our understanding of the phonological loop and chunking, word length, and similarity effects may impact on why the discrepancy between words and numbers occur. This is not suggesting that word lists or digit lists should not be used, but it indicates that comparing WM performance between tasks that have used numbers and words is not very reliable. Instead, words and digits should be used independently of one another to test the construct. For instance, while infinite, numbers share many similar characteristics making chunking easier. We is familiar with both small and large numbers and are able to chunk many numbers together to form one number, making it easier to remember. For example, if participants were given the digits, 5, 1, 9, 6, and 3 chunking is relatively easy and can be made into a familiar item such as, 5-1963, which could be remembered as a date, forming a large chunk that is easier to remember. Based on Miller (1956) and Cowan (2001) it is plausible that chunking could occur in this way due to numbers sharing common characteristics and able to be universally applied. Conversely, words cannot be chunked as easily as they do not share universal similarities, it is possible to chunk into categories (e.g., animals or vehicles), but when words are unrelated, chunking like this is not possible, making the task inherently more difficult.

2.1.1 Serial recall task

Recall is a key component of short-term memory methodology and is essential for testing the limits of WM and our ability to remember information or events. Retaining word order is a key function of WM. The ability to remember words in a serial order requires WM processing and maintenance. Generally, two types of recall are used when testing WM, free recall, and serial recall. Serial recall is where information or events are retrieved in the order they were presented or happened (Klein, Addis, & Kahana, 2005). Free recall is where information is retrieved in any order, regardless of the order of presentation (Klein et al.,
Recall measures tell us the limits of our memory systems and important information about how we remember items and events. While free recall and serial recall are different constructs, they do share some common characteristics.

Serial recall is when we remember information and events in the order they were presented or experienced. For example, if the words *cat, dog, bat, snake, ant, and rabbit* were presented they must be recalled in the same serial order: 1. *cat*, 2. *dog*, 3. *bat*, 4. *snake*, 5. *ant*, 6. *rabbit*. A typical outcome from employing a serial recall tasks is the serial position curve. This tends to elicit a strong primacy effect, where recall decreases (item errors increase) along the serial position, is flat through the middle, and elicits a recency effect where recall increases (item errors decrease) along the serial position. Generally, item recall is poorest during the middle items and remains flat (Baddeley, 2002; Gathercole, 2008; Murdock, 1962). Figure 2.1 shows a typical serial position curve with six items when the expected outcome is a strong primacy and recency effect. However, depending on the type of task (e.g., verbal recall), the recency effect may not be as strong (e.g., Allen & Hulme, 2006; Davis, Rame, & Hiscock, 2013; Logie, 2003; Pattamadilok et al., 2010, Saito et al., 2007; Spurgeon, Ward, & Matthews, 2014).
Serial recall experiments tend to yield both a primacy and recency effect, however there tends to be a stronger recency effect found in free recall tasks. This is not always the case as other variables such as the modality of output may also affect item recall. For example, recalling items verbally or writing them down may elicit alternative results.

Serial recall has many other benefits when analysing data as it enables researchers to assess the incorrect responses as well as correct response. Often in serial recall task mistakes occur in the form of order errors (Acheson & MacDonald, 2009; Henson, 1998)—that is, when an item is recalled correctly but in the incorrect serial position (Gathercole, 2008). Order errors are reported as they provide insight into how tasks affect the underlying processes of WM (Acheson & MacDonald, 2009). For example, if there was a high proportion of order errors, this would provide evidence that the task is preventing accurate phonological encoding (Acheson & MacDonald, 2009). Other errors include omissions, where no item is recalled for the corresponding serial position. Lastly, intrusions can be
measured, whereby an item is recalled that was not presented in the list, this may be an item from a previous list or an unrelated item. The number of correct items and order errors occurring in serial recall tasks also depends on how the items are scored.

In a majority of serial recall experiments a strict scoring criteria is employed, where an item is only marked correct if it recalled in the correct serial position. However, variants of scoring are used depending on the items being tested, the mode of presentation, and how the items are recalled. For example, if participants recalled items by writing them down on a scoring sheet where the designated positions are available a strict serial item scoring criteria may be employed. However, if the mode of recall was verbal where individual’s responses are recorded an alternative scoring method is sometimes employed. One alternative that has been used in serial recall task is the relative scoring method. This is where an item is recorded as correct if it directly followed an item from the previous serial position. For example, if a list contained the words *cat, dog, snake, ant, and rabbit*, during the recall phase if the participants recalled snake followed by ant, ‘ant’ would be scored as a correct response as it directly followed ‘snake’ in the serial position. It is important to note in the relative scoring method the first recalled item is always scored as a correct response (if the word was presented in the list). The relative scoring method is often used in oral recall, this is because strict serial recall may neglect the correct serial recall of later list items, where missing an item leads to all subsequent items being scored as incorrect. To overcome this limitation it is common to still employ a strict scoring method by instructing participants to indicate the word ‘BLANK’ if they cannot remember the item in the corresponding serial position, this allows the option to maintain word order.
2.1.2 Verbal serial recall

Verbal serial recall methods have been widely used in memory research and have utilised varying word list lengths, for example, with four, five, six, and seven serial positions (e.g., Acheson, MacDonald, & Postle, 2011; Acheson, Postle, & Macdonald, 2010; Allen & Hulme, 2006; Cowan et al., 2006; Davis, Rane, & Hiscock, 2013; Gathercole, 2008; Hurlstone, Hitch, & Baddeley, 2014; Logie, 1995; Logie, Della Sala, Wynn, & Baddeley, 2000; Logie, Della Sala, Laiacona, Chalmers, & Wynn, 1996; Miller & Roodenrys, 2012; Morey, Morey, van der Reijden, & Holweg, 2013; Mueller, Seymour, Keras, & Meyer, 2003; Pattamadilok, Lafontaine, Morais, & Kolinsky, 2010; Rudkin, Pearson, & Logie, 2007; Saito, Logie, Morita, & Law, 2008; Spurgeon, Ward, & Matthews, 2014; Tan & Ward, 2008).

Essentially, verbal serial recall requires participants to immediately repeat a list of words in the correct order, after hearing them (Allen & Hulme, 2006). While in common serial recall methodology (e.g., where words are presented visually or recalled through written responses) the recency effect is the most reliable outcome. In verbal serial recall (where words are presented auditorily or recalled verbally) the primacy effect tends to have a greater prominence, (e.g., Allen & Hulme, 2006; Davis, Rane, & Hiscock, 2013; Hurlstone, Hitch, & Baddeley, 2014; Logie, 2003; Logie, Della Sala, Wynn, & Baddeley, 2000; Pattamadilok et al., 2010, Saito et al., 2008; Saito, Logie, Morita, & Law, 2008; Spurgeon, Ward, & Matthews, 2014; Tan & Ward, 2008).

When recalling words in verbal serial recall, the words are typically said aloud. For example, if you hear the words “dog, cat, bat, elephant, rabbit, spider” then you are to recall them aloud in the same order you just heard. If you do not remember a word in a certain position you are to say the word ‘BLANK’. For example, if you do not remember the third word, you are to say “dog, cat, BLANK, elephant, rabbit, spider”. This type of recall technique has been utilised in more recent verbal serial recall studies (e.g., Acheson et al., 2010; Miller & Roodenrys, 2012; Tan & Ward, 2008, Tindle & Longstaff, 2016a, 2016b).
more recent years the use of recording devices in the room with the participant has allowed
the experimenter to be absent from the room, where previously the experimenter was present
and immediately scored the participant’s response. The use of recording devices reduces
experimenter bias; where an experimenter who thinks the person will perform poorly, will
give them a lower score, and will give another person who they think will perform well a
higher score, when the work produced is essentially identical. It also reduces the effect of
experimenter influence: Before recording devices, there was an extraneous influence from the
presence of the experimenter on the participants’ performance. Instead, participants would be
scored in the presence of the experimenter, as they were responding. The personal interaction
between experimenter and participant will influence the participant’s ability to respond (e.g.,
levels of anxiety, comfort etc. may differ). This ensures participant scores are more accurate
and allows a more reliable analysis of verbal serial recall data.

The pattern of results for verbal serial recall is characterised by a strong primacy
effect, flat performance during the middle serial position and a slight increase in performance
for the recency items. The expected pattern is outlined in Figure 2.2, in this example recall at
each serial position is presented as a proportion of correct responses (i.e., the number of
words recalled in the correct serial position divided by the number of word lists e.g. if there
are 5 lists and the first word was recalled in 4 out of 5 lists, the proportion recalled is 0.8).
Further examples of this pattern can be found in various verbal serial recall studies (e.g.,
Hurlstone, Hitch, & Baddeley, 2014; Logie, Del Sala, Wynn, & Baddeley, 2000; Saito, Logie,
2.1.3 Free recall tasks

Free recall is another method used for recording correct item responses, however there are no restriction on the order items are recalled, allowing participants to recall items in any order. Free recall also follows a similar serial position curve, however, contrary to serial recall a more prominent recency effect occurs. In free recall, participants are able to recall items in any order. It is understandable that recent items would be recalled initially in free recall as there are no restrictions placed on retrieval. It would be cognitively efficient to recall the least rehearsed items first before attempting the primary items which may have had significantly more time for rehearsal. It is important to note the recency effect of serial recall takes place
independently of free recall. In serial recall, the last items are recalled quite well even though they are recalled last, contrasting the recency effect of free recall where the last items are often recalled first (Page & Norris, 1998).

Free recall is a less common measure of WM and tends to receive criticism about its effectiveness to measure WM accurately. Baddeley (1976) suggested free recall is a better measure of long term memory, while it shares a common characteristic in the recency effect it may not be the most effective measure of WM processes. However, some research has investigated the effectiveness of free recall in measuring the constructs of WM (e.g., requiring phonological processing) and have found it essentially measures the same processes (Unsworth & Engle, 2007). Overall, the consensus in the literature indicates free recall does not result in any manipulation of information and is not a reliable measure of WM. While it may measure the same constructs as serial recall, the lack of manipulation and executive processes may suggest it is not an effective or appropriate method to investigate WM processes.

The use of both free recall and serial recall in testing the limits of WM and phonological processes is becoming more common (Baddeley, 2012; Chen & Cowan, 2005; Pattamadilok, Lafontaine, Morais, & Kolinsky, 2010; Ward, Tan, & Grenfell-Essam, 2010). However, there appears to be limitations in their use. For example, free recall paradigms typically elicit a recency effect where the number of words recalled becomes skewed towards to most recently presented items. This creates an effect that does not properly represent the processes of WM, because there is no need to retain word order as in serial recall.

Serial recall also has limitations, however, it allows the manipulation of items where the item and serial position must be retained in WM (Chen & Cowan, 2005). This draws upon higher order executive functioning utilising the central executive, essentially testing the limits of WM rather than eliciting LTM processes commonly associated with free recall (Baddeley, 1976).
The role of serial order is an essential mechanism of testing WM (e.g. Acheson et al., 2011; Baddeley, 2000, 2002, 2003, 2012; Bublak et al., 2002; Burgess & Hitch, 1999; Chen & Cowan, 2005, 2009; Cowan, 2001; Gathercole, 2008; Henson, 1998; Lekeu et al., 2010; R. H. Logie, Della Sala, Wynn, & Baddeley, 2000; Mueller, Seymour, Kieras, & Meyer, 2003; Oberauer, 2003; Page & Norris, 1998; Pattamadilok et al., 2010; Repovs & Baddeley, 2006; Ward et al., 2010). Therefore, the testing of WM should employ a design that best manipulates and controls for this key component. While free recall has been used to test WM, the recall of items tends to elicit a strong recency effect making it more vulnerable to confounding variables such as word length, list length, and lexical effects. Based on the evidence presented it would be plausible to suggest serial recall would be the most efficient methodology to employ when testing WM processes. The serial recall specifically requires executive processes to hold items in articulatory store while maintaining the serial position of each item. It is important to note that free recall still utilises phonological processing, however, the demand placed on WM is significantly less than serial recall, as it seems to rely more on LTM processes rather than WM.
2.2 Fine motor movement (handwriting and drawing)

Analysing fine motor movements such as handwriting and drawing have become prominent in recent decades. Advancements in technology allow us to collect data previously unattainable, the use of computer programs allows the analysis of writing and drawing through recording the kinematic components of movements. This allows a more valid and reliable measure of recording the fluency of fine motor movements.

Methodology surrounding fine motor movements usually focuses on analysing the kinematics of an individual’s handwriting or drawing (e.g. Braswell & Rosengren, 2000; Bryant, Rintala, Lai, & Protas, 2010; Hudson & Farran, 2011; Longstaff & Heath, 2000, 2003, 2006; Slavin, Phillips, & Bradshaw, 1996; Tucha, Mecklinger, Walitza, & Lange, 2006; Tucha, Walitza, et al., 2006; Willingham, 1998). Some common stimuli are used across a majority of studies with handwriting analysis usually measuring an individual’s writing of words, sentences, or letters. Many studies require participants to continually write the letters ‘el’ in cursive writing. Writing e’s and l’s are useful as they have similar movements to general handwriting. However, they do not accurately resemble some letters, for example, crossing your t’s or dotting your i’s. The movements needed to produce e and l combinations ensure the pen is touching the writing pad or paper at all times and a reliable measure of movement can be analysed (Bryant et al., 2010; Slavin et al., 1996; Tucha et al., 2006; Tucha & Lange, 2001, 2004, 2005; Tucha, Mecklinger, et al., 2006). Using ‘e’ and ‘l’ loops allows the experimenter to measure the smallest relevant automated handwriting movement (a single stroke), with a single peak in velocity (Tucha et al., 2006; Mai & Marquardt, 1992). This method enables a control of handwriting movements and can eliminate individual variability in handwriting. This enables an accurate measure of the different kinematic variables that are related to handwriting fluency. Using writing is useful as it is an overlearned skill (Longstaff & Heath, 1997).
In analysing handwriting movements using drawings, a common methodology is to analyse the kinematics of simple (e.g., circle, triangle, square and asterix) and complex drawings (e.g., house, face, sun, multiple shapes within one another) which are essentially combinations of the simple shapes (e.g., Braswell & Rosengren, 2000; Hudson & Farran, 2011). This enables a comparison between how handwriting movements can differ based on the different types of movements that are made during handwriting. For example, using discrete movements that require pauses in movement and acute changes in direction, speed, and size (e.g. drawing a five-pointed star) as opposed to continuous movements that require a constant fluid movement and maintenance of velocity or motion (e.g. drawing a circle).

The movement analysis is often used to determine fluency of movements as measured by specific kinematic variables. The kinematic measures used to analyse fluency are focused around measuring what is considered the smallest component of the movement, known as a ‘stroke’ (Tucha & Lange, 2005). A stroke is the smallest meaningful measure of handwriting movement between points of zero velocity or local minima of absolute velocity (Tucha et al., 2006). When writing, several strokes may be programmed as a sequence of movements or the following stroke may be programmed during or after the current stroke (Teulings, 1996). To determine handwriting fluency, the averages of an individual’s stroke components are recorded and analysed (e.g. Teulings, Contreras-Vidal, Stelmach, & Adler, 1997; Tucha et al., 2006; Tucha & Lange, 2004, 2005; Tucha, Walitza, et al., 2006).

The common variables used amongst handwriting and drawing methodology are the dimension of the stroke length, usually measured as the average length of a stroke in $mm$ and the stroke duration, the mean length of time taken to complete a stroke. The kinematics of each stroke are also analysed through measuring the averages of the peak velocity i.e. the maximum speed in mm/s a stroke reaches. The time taken to achieve peak velocity; this measure tells us the amount of acceleration is occurring in each stroke. The time taken from peak velocity to zero is also recorded this shows the amount of deceleration occurring
between each stroke. Average normalised jerk (ANJ), is a common measure related to the
corelation and smoothness of a movement, for example, high average normalised jerk is
reflective of dysfluent movements (Caligiuri, Teulings, Dean, Niculescu, & Lohr, 2011). To
analyse the efficiency a movement the proportion of time accelerated calculated by dividing
the time taken to achieve peak velocity by stroke duration (Nagasaki, 1989; Slavin et al.,
1996), this is also a strong predictor of writing fluency, smaller discrepancies in velocity
reflect more fluent handwriting (Meulenbroek & Van Galen, 1988; Tucha & Lange, 2001).
Stroke consistency is also another measure calculated to show how reliable an individual’s
stroke is, a reliable movement would have high consistency while a low consistency suggests
the movement was not reliably produced (Nagasaki, 1989; Slavin et al., 1996).

Furthermore, additional kinematic measures are used to analyse handwriting such as
the total writing time (ms) (including all strokes) and the total distance the stylus tip travelled
on the surface while writing (mm) (Tucha et al., 2006; Tucha & Lange, 2004, 2005). Similar
to above, other studies have also employed different variables to measure handwriting fluency
across each stroke. The average stroke velocity, acceleration, duration, and size are measured
to assess the fluency of handwriting (e.g. Schenk, Walther, & Mai, 2000; Teulings et al.,
Tucha, Mecklinger, et al., 2006; Tucha, Walitza, et al., 2006). It is also important to note
strokes can be divided into up strokes and down strokes; down strokes are reliable measures
of letter formations while upstrokes tend to represent the connection between letters within
words (Tucha & Lange, 2004). The measure of velocity is a key variable in measuring writing
fluency.

In movement analyses of drawing and some writing studies the accuracy of the items
is also analysed through visual inspection from experimenters and experts. The accuracy of an
item can be defined by the consistency of the participants drawing compared to the stimuli or
alternatively how well the participants has stayed within the parameters of the experimental
criteria. For example, Bryant et al. (2010) analysed the handwriting length (mm) of individuals with Parkinson’s diseases. Participants were instructed to write immediately after (1) practising writing between parallel lines; (2) after practising writing with grid lines; and (3) practicing writing without lines (control condition). Participants were instructed to touch the letters on the upper and lower parallel lines or to touch each letter on all four walls of a grid. The participant’s fluency can be measured by how well they stayed within the boundaries of the writing lines or grid, as per instructions. Bryant’s findings identified that there was no difference in handwriting fluency when writing between parallel lines or grid lines, but both were better than free writing (no lines). The analysis of fluency also utilises the kinematic variables outlined in the analysis of handwriting, which is the kinematics of the average strokes (Braswell & Rosengren, 2000; Bryant et al., 2010; Hudson & Farran, 2011).

The common methodology of handwriting aims to identify the kinematic components that best represent fluency. The above methodologies use words, letters, and shapes to analyse the fluency of handwriting across many variables measuring, speed, shape, and accuracy of the movements. The analysis of movement has been used to analyse performance and deficiencies in many areas including child development (Accardo, Genna, & Borean, 2013; Tucha & Lange, 2005), brain injuries (Hogan & Sternad, 2007), and movement disorders (Caligiuri, Teulings, Dean, Niculescu, & Lohr, 2011; Longstaff & Heath, 2006; Mergl, Tigges, Schröter, Möller, & Hegerl, 1999; Smits et al., 2014; Teulings & Stelmach, 1991). The continual use of this methodology will be beneficial for investigating the role and connection between fine motor movements during handwriting and drawing, and WM.
2.3 General methodology employed in thesis

In this chapter I have identified some of the key methodologies used to test verbal WM and handwriting. To test the performance of both tasks when performed simultaneously, a verbal serial recall methodology is employed. This allows us to verbally present word lists to participants and allow them to write them down as they hear them, in real time. This allows an interpretation of the effect of handwriting during the encoding (processing and maintenance) stage of working memory. In Chapter 3, I employ this methodology to establish if a handwriting task reduces verbal serial recall performance compared to a reading and listening task. My thesis is concerned with how handwriting reduces WM performance when the two tasks are performed simultaneously. To measure the performance of both handwriting and WM and the impact on one another when performed simultaneously, a serial verbal recall task will be implemented. Whereby participants will write down lists of words before recalling them in a verbal serial recall task.

Design

The experiments I have designed in this thesis all employ a repeated measures design. The dependent variables are the proportion of words recalled correctly at each serial position and the proportion of order errors (Allen & Hulme, 2006; Murdock, 1976). Participant recall is measured by correct responses following strict serial recall criteria (Acheson, MacDonald, & Postle, 2011; Acheson & MacDonald, 2009; Conway et al., 2005), that is, a correct response was recorded if a word was recalled in the correct serial position. Mean accuracy for each serial position for each participant was used for further analysis. Order errors (words recalled correctly but in the incorrect serial position) were analysed as the proportion of order errors in each condition. This is calculated by subtracting total serial recall from the overall recall of words (i.e. free recall scoring) in each condition. The total order errors are then divided by the total words recalled in any position and given as a proportion of order errors.
Typically, the experiments included three conditions; a listening condition, a handwriting condition, and a pseudo-writing or drawing condition.

For all experiments, handwriting kinematics are recorded to assess changes in handwriting or pseudo-handwriting as measured by the average stroke duration (ASD) i.e. the average duration of a single movement (stroke) in seconds. Average stroke size (ASS) i.e. the average size of a single stroke (cm). Average absolute velocity (AAV) i.e. the speed of movement is measured as cm/second. Average normalised jerk (ANJ), which is a measure of the control and smoothness of a movement, for example, high average normalised jerk is reflective of dysfluent movements (Caligiuri, Teulings, Dean, Niculescu, & Lohr, 2011). When I refer to handwriting fluency, I will be looking for relative changes in average stroke duration (fast strokes; seconds), stroke sizes (cm), relatively high average absolute velocity (cm/sec), and average normalised jerk. Tucha et al., (2006), measured handwriting kinematics as measure of fluency by increases in velocity, acceleration, and size. The analysis of handwriting kinematics and further literature on these variables is outlined in Chapter 5.

Apparatus

The experiment was conducted in a lab environment and were conducted using a personal computer (screen resolution, 1680 x 1050) and a Wacom (Intuos3, 12”x19”, model PTZ-1231W) digital writing pad and pen (stylus) to record the movements of participants (e.g. chapter 1, 2, and 8); or with a Microsoft surface pro and stylus to display the stimuli and record the movements of participants (e.g. chapter 3, 4, 5, 6, and 7). MovAlyzeR (Neuroscript LLC, USA) displayed the movements on a computer screen and recorded the pen movements. The participants were given a pair of headphones to listen to a pre-recorded list of words spoken by the researcher, also presented via MovAlyzeR.

Words were obtained from the MRC psycholinguistics database (Coltheart, 1981b). The parameters set for the words were the number of letters (4 - 8), syllables (2), word
familiarity (300 - 500), concreteness (200 - 500), and the Kucera and Francis (1967) frequency scale (1 - 75). The original search returned 350 words, which were then randomised and the first 270 words were chosen, the word list can be found in Appendix B. The words were portioned into three blocks of 15 lists, with 6 words per list. The blocks of words were counterbalanced across conditions, and the order of conditions was counterbalanced. That is, all three conditions contained every word block. The word blocks were organised and counterbalanced ensuring the same word block was not presented in the same experimental condition. The counterbalancing of the condition/block order was then randomised so every version of the presentation had an equal chance of being used. The conditions were counterbalanced so no participant had the same combination of word lists/condition. As the experiment was repeated measures, participants completed all three conditions. Each condition contained 15 lists of 6 words, in total there were 90 words presented in each condition. There was a total of 45 possible lists of words that could be presented in each of the conditions.

It is worth emphasising that the general structure of each experimental condition was the same, what changed is the secondary task they performed while listening to words. For each condition, there were 15 lists of 6 words, presented to the participant using MovAlyzeR. At the start of each condition a ‘START’ icon appears. To start a list of words participants made a single stroke movement through the ‘START’ icon using the stylus. This triggered the beginning of a word list. Between hitting the ‘START’ icon and the presentation of the first word was a 1.5-second gap, then the presentation of the first word occurred. The next five words were presented at 3-second intervals. After the last word had been presented, there was a final 3-second gap and a beep was used to signal to the participant to stop the task they were doing. At this point, the writing/drawing that the participants produced disappeared from the screen so they could not refer to the written output for recall purposes. Recall was prompted by a new screen that had ‘RECALL’ written on the center of the screen, this lasted for 30 seconds before
a new ‘START’ icon was displayed indefinitely until the participant was ready to continue (i.e. participants could continue to recall after the 30 seconds if they needed to). Participant’s voices were recorded using an Olympus Digital voice recorder (VN-8500PC).

In this chapter I have identified some of the key methodologies used to test verbal WM and handwriting. To test the performance of both tasks when performed simultaneously, a verbal serial recall methodology is employed. This allows us to verbally present word lists to participants and allow them to write them down as they hear them, in real time. This allows an interpretation of the effect of handwriting during the encoding (processing and maintenance) stage of working memory. In Chapter 3 I employ this methodology to establish if a handwriting task reduces verbal serial recall performance compared to a reading and listening task.
Chapter 3 – Writing, reading, and listening differentially overload working memory performance across the serial position curve.

This chapter has been adapted from the publication:

Working Memory (WM) is a limited capacity system devoted to the temporary storage, retrieval, and manipulation of information during a variety of cognitive processes (Baddeley, 2000; Baddeley & Hitch, 1974). WM also plays a significant role in our ability to process and perform complex cognitive tasks such as listening, reading, and writing (Olive, 2004; Tirre & Peña, 1992). Baddeley (2003, 2012) maintains that WM consists of four systems: The central executive is responsible for devoting attentional processes to three sub-systems. The first sub-system is the phonological loop, which is responsible for the temporary storage of verbal information (written or spoken). The visuo-spatial sketchpad is responsible for temporarily storing visual and spatial information such as colour, speed, shape, and movement. The final sub-system is the episodic buffer (Baddeley, 2000), which is controlled by the central executive and is able to process and integrate multi-coded information (phonological, visual, spatial, and long-term memory).

The multi-coded nature of WM enables the integration of information from the phonological loop, visuo-spatial sketchpad, and long-term memory to aid in problem-solving (Baddeley, 2000, 2001). Baddeley (2012) also explains that the central executive plays a prominent role in directing attentional resources to the phonological loop, suggesting both systems play a key role in learning verbal and written information. When processing verbal information, the phonological loop is able to store phonologically coded information directly into temporary storage. However, due to WM’s limited available capacity it can become overloaded during cognitively complex tasks (McCutchén, 1996, 2000; Olive, 2004; Peverly, 2006; Schweppe & Rummer, 2013).

Attention is also a limited capacity resource that is integral to WM processes such as encoding and maintenance (Barrouillet & Camos, 2007; Chun, 2011). Chun (2011) investigated the relationship between visual WM and visual attention. Despite identifying that both of these operate independently and are limited in capacity, the performance of the tasks
was determined by how well distractions could be inhibited. The ability to sustain and direct attention towards relevant items is important for successful WM performance when faced with both internal and external distractors. Furthermore, when performing WM tasks, we switch our attention and resources between the encoding and maintenance of to-be-remembered information, as explained by the TBRS model (Barrouillet & Camos, 2007). According to this model, if attentional resources are diverted away from one process (e.g., encoding the words), they cannot be effectively used for that process as they are now being used for the process they are diverted to (e.g., maintenance). Barrouillet and Camos also demonstrated that there is a greater decline in WM performance the longer a secondary process captures attention. This suggests that when attention is captured by a secondary task it can prevent attention from being directed towards WM encoding and maintenance. If the secondary task can be inhibited and/or does not substantially capture attention, WM performance will be more successful. The aim of the current study is to investigate whether handwriting while concurrently completing a verbal serial recall task reduces WM performance compared to reading and listening.

Listening is a relatively simple task that places little strain on WM when required to process, rehearse, and retrieve information within the phonological loop (Christensen et al., 2012, Margolin, Griebel, & Wolford, 1982). When verbal information is heard (e.g., while listening to speech) it can be stored directly into the phonological loop as it is phonologically coded (Baddeley & Larsen, 2007; Haenggi & Perfetti, 1992). However, WM is still limited in its capacity to store information and not all verbal information enters the phonological loop (Chen & Cowan, 2009). This may occur when the central executive must divide attention between two cognitive processes, for example, when there are dual tasks (Barrouillet & Camos, 2007; Unsworth & Engle, 2007). It can also occur if a distraction interrupts sub-vocal rehearsal such as when two verbal tasks occur simultaneously (e.g., speaking while listening to a conversation), resulting in articulatory suppression (Chen & Cowan, 2009; Oberauer &
Lewandowsky, 2008). The addition of tasks that cause articulatory suppression and divide attention may contribute to overloading WM capacity, resulting in poor verbal WM performance. Listening by itself appears to be a relatively simple task. Other verbal tasks such as reading also utilise the phonological loop but can be seem as relatively more complex.

The cognitive processes involved during reading appear to be more complex than those occurring during a listening task (Margolin et al., 1982; Rayner, Pollatsek, Ashby, & Clifton, 2012). When reading, information must be converted into a phonological code before being temporarily stored in the phonological loop (Baddeley, 1997; Sadoski & Paivio, 2004). This is theorised to occur through the articulatory control process by sub-vocalising the written material (Lewandowsky & Farrell, 2006; Page & Norris, 1998; Tan & Ward, 2008). This creates an additional step for the reading process before the words can be temporarily stored, which places greater strain on WM (Davidson, 1986). This increase in complexity may be due to the phonological loops’ inability to transform written material into a phonological code efficiently during complex tasks (Besner & Davelaar, 1982; Folk, 1999). Research has shown that cognitive resources devoted to reading can overload WM’s capacity to store and immediately recall information (Linderholm, Xiaosi, & Qin, 2008; McCutchen, 2000; Olive, 2004; Peverly, 2006). In contrast to listening, the reading process appears to be relatively more complex due to the additional transformation of the words into a phonological code. Complexity can also be increased in other ways, such as when required to write down information while listening, raising the demands on WM processes.

When listening to verbal information that we might want to later recall (e.g., during a lecture) it is common to write down key points as we hear them. However, the production of written material places significant cognitive demands on WM and can hinder the recall of to-be-remembered information (Bourdin & Fayol, 1994; Kellogg, 1996, 2001; Klein & Boals, 2001; McCutchen, 1996, 2000; Olive, 2004; Peverly, 2006). Our ability to store information in WM seems to be impaired when an individual is asked to write down information while
Writing, Reading, and Listening

listening (e.g., Bourdin & Fayol, 1994; McCutchen, 1996; Peverly, 2006). Peverly attributes this to the complexity of the writing process, as it requires a high level of cognitive effort. This places extra strain on WM, inhibiting its processes and our ability to store information (McCutchen, 2000). Writing is a cognitively complex task requiring greater effort, overloading WM and its capacity to store verbal information as well as devote processes to writing. However, these studies have not identified if the relative complexity of writing reduces WM performance compared to just listening to information or reading information when information must be immediately recalled.

Kellogg (1996) produced a model of writing and WM showing the interrelation between the two processes to identify that they share a common resource. Kellogg suggested writing loads on WM processes because we must plan, execute, and monitor written output. When planning to write, verbal WM is activated to plan the phonetics of the words (e.g., spelling, letters, sounds, and syllables). In addition to this, the movement requirements are planned within visuo-spatial WM to produce legible letter shapes and maintain the correct spatial sequence of letters. After the planning stage, the written output is executed and is the responsibility of the central executive (Kellogg, 1996). During execution, constant visual feedback is required to edit and maintain the written output to ensure what has been written and what comes next will be correct (Kellogg, 1996). Any errors or perceived errors are rectified and adjustments in motor movements and/or the phonetics of the words are made. Recent research has further demonstrated that handwriting is a complex motor task that requires visual feedback to be executed efficiently (Tse, Thanapalan, & Chan, 2014). Kellogg’s model showed that writing and WM share a common resource as well as identifying how the different writing processes utilise verbal, visual, spatial, and executive processes within WM.

The above research suggests that both reading and writing may overload WM processes resulting in poor storage and retrieval of information while listening places minimal
strain on WM. However, previous studies have failed to investigate whether handwriting, reading, and listening place different levels of strain on WM and if any of them places significantly more strain than the others. Specific to the current study, Bourdin and Fayol (1994, 2002) found that participants recalled fewer words in a serial recall task when they wrote down words compared to if they verbalised their responses by saying them aloud. While these findings are consistent with other findings on the complexity of handwriting (e.g., McCutchen, 2000; Olive, 2004), it fails to determine if handwriting during encoding (i.e., when the words were initially presented) overloads WM’s ability to immediately recall information more than reading or listening during encoding. This is important, as it will identify if handwriting results in a decline in WM performance when the tasks are performed simultaneously, as well as showing if interference also occurs during encoding as opposed to retrieval. Writing appears to be more cognitively complex than reading and listening. We would therefore expect it to overload WM to a greater extent. However, this proposal has so far not been investigated.

To investigate whether reading, handwriting, and listening impact on recall to different degrees the current study asked participants to complete a serial recall task after they read, listened, and wrote down lists of words. It is expected that serial recall will differ between all three conditions, with recall being best in the listening condition, moderate in the reading condition and poorest in the handwriting condition. Further post hoc analysis will be conducted of the serial position curve to investigate whether this pattern holds between all the conditions at individual serial positions. This will provide more fine-grained information about how the WM processes are affected by the tasks.

As I will be employing a serial recall task it is possible that mistakes will occur in the form of order errors (Acheson & MacDonald, 2009; Henson, 1998)—that is, when an item is recalled correctly but in the incorrect serial position (Gathercole, 2008). Order errors will therefore be reported as they provide insight into how each task is affecting the underlying
processes of WM (Acheson & MacDonald, 2009). For example, if the handwriting condition produces a higher proportion of order errors, this would provide evidence that the secondary handwriting task is preventing accurate phonological encoding (Acheson & MacDonald, 2009).

Methods

Participants

Sixteen university students participated in this experiment. After checking for outliers, one of these participants was rejected from further analysis, confirmed through boxplots and extreme z-score (+3.29). This left 15 participants, seven males and eight females; with a mean age of 34.67 years ($SD = 12.45$). All participants were required to have normal or corrected to normal vision and hearing with English as their first language. Participants provided informed consent and the study was approved by the Southern Cross University Human Research Ethics Committee.

Design

The experiment employed a repeated measures design. There were two independent variables: experimental condition, with three levels (reading, listening, and handwriting), and serial position, with six levels (position 1 to 6). The dependent variables were the proportion of words recalled, and the proportion of order errors. Participant recall was measured by correct responses following strict serial recall criteria (Acheson, Postle, & MacDonald, 2010; Conway et al., 2005). That is, a correct response was recorded if a word was recalled in the correct serial position. Mean accuracy for each serial position for each participant was used for further analysis. Order errors were analysed as the proportion of errors individuals made per condition. This was calculated by dividing the total number of order errors by the number of words recalled correctly in any position (Miller & Roodenrys, 2012).
Apparatus

The experiment was conducted in a lab with a personal computer (screen resolution, 1,920×1,080) and a Wacom (Intuos3, 12”×19”, model PTZ-1231W) digitizer and stylus to record the words written by the participants. MovAlyzeR (Neuroscript LLC, USA) displayed the handwriting on a computer screen and recorded the pen movements. The participants used headphones to listen to a pre-recorded list of words spoken by the researcher, presented via E-prime on a second computer.

Three hundred and fifty words were obtained from the MRC psycholinguistics database (Coltheart, 1981b). The parameters set for the words were the number of letters (4-8) and syllables (2), word familiarity (300-500), concreteness (200-500), and the Kucera and Francis (1967) frequency scale (1-75). The words were randomised using excel and the first 270 words were chosen. The words were portioned into three blocks of 15 lists, with six words per list. All three conditions contained every word block, the word blocks were organised and counterbalanced ensuring the same word block was not presented in the same experimental condition. The counterbalancing of the condition/block order was then randomised so every version of the presentation had an equal chance of being used. The conditions were counterbalanced so no participant had the same combination of word lists/condition. As the experiment was repeated measures, participants completed all three conditions.

The general structure of each condition was the same (i.e., words were presented then recalled). What changed was the task the participants performed. At the start of each condition a “START” icon appeared. To start a list of words participants needed to make a single stroke movement through the “START” icon using the stylus. This would trigger the beginning of a word list, between hitting the “START” icon and the presentation of the first
word was a 1.5 s gap, then the first word was presented (auditory or visual). All the words were recorded by the researcher using Audacity (2014) and the files were saved as .wav files. The mean duration (presentation) of each individual word in the listening and handwriting condition was 916 ms ($SD = 102$ ms). The words in the reading condition were presented for 1 s before disappearing from the screen. For each condition, the next five words were presented at 3 s intervals, measured from the beginning of each word presentation. After the last word had been presented, there was a final 3 s gap and a beep to signal to the participants to stop the task they were doing. The total length of each word list was 18 s, after which the screen was cleared of any writing to prevent participants from gaining feedback to aid in recall. At this point, recall was prompted by a new screen that had “RECALL” written on the centre of the screen. This lasted for 30 s before a new “START” icon was displayed until the participant was ready to continue (participants could continue to recall after the 30 s if they needed to).

Recall was recorded using a response sheet with positions one to six. During the recall phase of the experiment participants were required to write down their responses by filling in the spaces provided with the word that corresponded with that serial position.

Procedure

Participants completed the experiment individually. Upon entering the room, participants were greeted by the experimenter and were asked to take a seat in the cubicle where the experiment was to take place. Participants were asked to read the information sheet that outlined the purpose of the experiment, what would be required of them as well as instructing them of their rights to participate and withdraw. Participants then completed a consent form, which was signed and dated. The participants were then instructed on how the program worked and what they needed to do during the experiment.
Once this was completed, the experimenter instructed the participants that they were going to complete a WM task. Firstly, the participants were asked to place the headphones on and then a practice example was opened on MovAlyzeR and the experimenter walked the participant through the procedure. Participants were told they were going to complete a serial recall task. They were instructed that they would hear a list of words (listening and handwriting conditions) or read a list of words (reading condition). At the end of each list of six words there was a screen displaying “Recall”. Once this appeared, participants were told to recall the word lists by writing them down on the response sheet provided. They were given the example, if you were to hear/read the words dog, cat, bat, elephant, rabbit, and spider you are to recall them by writing them down in the same order you just heard or read, in the blank spaces provided. If you do not remember a word in a certain position, you are to leave that space “BLANK”. For example, if you do not remember the third word, you are to write, “Dog, cat, _____, elephant, rabbit, and spider”. Participants were told that each list had exactly six words and that there were fifteen lists in each condition. The procedure for recall was the same for all conditions.

Next, the participants were shown the “START” icon and told that throughout the experiment to start a new list they must move the stylus through the “START” icon. After doing this, they would hear/read a new list of words. Participants practiced before the start of each condition until they and the experimenter was comfortable with the program. At this point, the experimenter started the experimental condition and left the room. Participants were asked to contact the experimenter once the condition had been completed (this would be noticeable as the program shut after completion).

When completing the listening task, participants were asked to focus on an “X” that appeared at the centre of the screen after placing a stroke through the “START” icon. Once the word list had ended, the word “RECALL” appeared on the screen and participants were told that this was where they were to begin recalling the words in the order they were
presented. It was emphasised that all they needed to do was listen to the word lists and once recall appeared on the screen to begin to write down their responses on the provided response sheet.

During the reading condition participants were instructed to silently read the words that appeared on the screen in front of them after hitting the “START” icon. Participants continued to read until the word “RECALL” appeared at the centre of the screen; this was to prompt them to stop and begin to write down their responses on the response sheet.

In the handwriting condition, participants were instructed to move the stylus through the “START” icon to initiate each trial. They were then instructed to write down the words they were listening to, beginning immediately as the first word was presented. Participants were told to write in their natural handwriting and attempt to write down each word even if they were unsure of the correct spelling. It was emphasised that they must attempt to write down each word. Participants continued writing until the end of the list (i.e., 3 s after the final word was initially presented). At this point, the screen went blank and “RECALL” appeared on the centre of the screen. Participants could then begin to recall the words on the provided response sheet, by picking up the pen.

**Results**

Recall was compared for all three experimental conditions (reading, handwriting, and listening) and serial positions through a repeated measures Analysis of Variance (ANOVA). The proportion of order errors were analysed with a repeated measures ANOVA to identify if there were significant differences between conditions. The descriptive statistics for the average number of words recalled (out of six) in the listening, reading, and handwriting conditions are provided in Table 3.1.
Table 3.1  
Mean number and standard deviation (SD) of words recalled per list (out of 6) in the listening, reading, and handwriting conditions

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Listening</td>
<td>3.76</td>
<td>1.04</td>
</tr>
<tr>
<td>Reading</td>
<td>3.51</td>
<td>1.06</td>
</tr>
<tr>
<td>Handwriting</td>
<td>2.82</td>
<td>.74</td>
</tr>
</tbody>
</table>

Word recall

Shapiro-Wilk’s and $F_{\text{max}}$ analysis was used to test the assumptions of normality and homogeneity of variance, respectively. Shapiro-Wilk’s was not met for four variables, recall at serial position one in the reading condition, position one and six in the listening condition and position six in the handwriting condition. As there were few deviations from normality, they were considered not to be of concern (Allen & Bennet, 2010). $F_{\text{max}}$ was not violated and homogeneity was assumed.

Mauchly’s test was significant for serial item recall indicating assumptions of sphericity were not met, thus the Huynh-Feldt adjusted analysis was employed. Mauchley’s test was non-significant for the experimental conditions indicating assumptions of sphericity were met. Figure 3.1 summarises the mean words recalled in the handwriting, reading, and listening conditions at each serial position. On average, participants recalled fewer words in the handwriting condition at serial positions one to three compared to the reading and listening conditions. However, recall in the reading condition at serial positions five and six was less than the handwriting and listening conditions.
Figure 3.1. The mean proportion of words recalled correctly at each serial positions in the listening, reading, and handwriting conditions. Error bars represent the standard error of the mean. Points are offset horizontally so that error bars are visible.

The repeated measures ANOVA revealed a main effect for experimental condition, $F(2, 28) = 14.59, p < .001, \eta_p^2 = .51$ and serial position, $F(1.90, 26.56) = 8.163, p = .002, \eta_p^2 = .38$. Bonferroni post hoc comparisons revealed that participants recalled significantly fewer words overall in the handwriting condition compared to the reading, $M_{Diff} = -.115$, Bonferroni 95% CI $[-.19, -.04]$, and listening conditions, $M_{Diff} = -.156$, Bonferroni 95% CI $[-.24, -.07]$. There was no significant difference between the reading and listening conditions.

The ANOVA also revealed a significant interaction between experimental condition and serial position, $F(10, 140) = 2.615, p < .001, \eta_p^2 = .38$. Further post hoc comparisons were conducted to determine at which serial position the differences occurred. A series of linear contrasts revealed a significant difference between the handwriting condition and the listening condition at serial positions one, $M_{Diff} = -.33$, Bonferroni 95% CI $[-.50, -.17]$, two, $M_{Diff} = -.31$, Bonferroni 95% CI $[-.44, -.18]$, and three, $M_{Diff} = -.26$, Bonferroni 95% CI $[-.41,
Recall was worse for the handwriting condition at serial positions one, $M_{\text{Diff}} = -.44$, Bonferroni 95% CI $[-.56, -.32]$, two, $M_{\text{Diff}} = -.33$, Bonferroni 95% CI $[-.47, -.20]$, and three, $M_{\text{Diff}} = -.30$, Bonferroni 95% CI $[-.48, -.12]$.

A significant reduction in item recall for the reading condition compared to handwriting occurred at serial positions five, $M_{\text{Diff}} = -.20$, Bonferroni 95% CI $[-.36, -.04]$ and six, $M_{\text{Diff}} = -.31$, Bonferroni 95% CI $[-.44, -.17]$. A reduction in the proportion of items recalled between the handwriting and the listening conditions was found at serial positions five, $M_{\text{Diff}} = -.18$, Bonferroni 95% CI $[-.29, -.08]$ and six, $M_{\text{Diff}} = -.31$, Bonferroni 95% CI $[-.48, -.15]$. There was no significant difference between reading and listening conditions at serial positions one, two, or three, or between the listening and handwriting conditions at serial positions five and six. There were no significant differences between any conditions at serial position four.

Order errors

Order errors were analysed as the proportion of errors individuals made per condition. Order errors were calculated by subtracting the total serial recall from the overall recall of words (i.e. free recall scoring) in each condition. The total order errors are then divided by the total words recalled in any position and given as a proportion of order errors. Figure 3.2 summarises the mean proportion of order errors in the handwriting, reading, and listening conditions. The repeated measures ANOVA revealed a significant difference in the proportion of order errors between conditions, $F(2, 28) = 13.51, p < .001, \eta^2_p = .49$. Bonferroni post hoc comparisons revealed that there were significantly more order errors in the handwriting condition compared to the listening condition, $M_{\text{Diff}} = .12$, Bonferroni 95% CI [.04, .2] and the reading condition, $M_{\text{Diff}} = .10$, Bonferroni 95% CI [.03, .17]. The listening and reading conditions did not differ.
**Discussion**

This experiment investigated how the relative complexity of listening, reading, and handwriting during encoding of verbal information affects WM performance on a serial recall task. The results suggest that the handwriting process overloaded WM significantly more than just reading or listening when trying to encode words in memory. This pattern was also found between conditions at individual serial positions. However, differences only occurred at serial positions one to three between handwriting and both reading and listening. At position four, there was no difference, and at position five and six, there was no difference between handwriting and listening, but a significant difference between handwriting and reading, with more words recalled in the handwriting condition. This finding supports previous literature indicating that the writing process is cognitively complex. Taken together, the results support...
the hypothesis that handwriting overloads WM and reduces recall performance compared to a listening and reading task.

The above results could be explained by the capacity of WM that is available for the recall task. The current study suggests listening places significantly less strain on WM (is less complex) than handwriting. This is consistent with previous research on the simplicity of listening tasks (Margolin et al., 1982) and the processing of phonologically coded material in WM (Baddeley, 2001). The listening condition also displayed typical primacy and recency effects. As such, listening does not overload WM more than reading and handwriting. It appears that during the listening task participants were able to recall more words as they were able to devote more cognitive resources to sub-vocal rehearsal, as information was phonologically coded and could be directly stored in the phonological loop. Additionally, during the listening task, participants could direct attention towards processing and maintenance because no secondary process was being performed (Barrouillet & Camos, 2007). This allowed attention to be sustained on the to-be-remembered items without the need to inhibit distractors (Chun, 2011).

There was no difference for overall recall between the reading and listening tasks. However, the expected difference did occur at serial positions five and six, with more words recalled in the listening task. The results demonstrate a typical primacy effect and a weaker recency effect for reading. The difference between the reading condition compared to the listening and handwriting conditions at these serial positions provides evidence that there are differences in the processing of the two types of verbal information (i.e., written and auditory). The results suggest that the processing of words in the reading task is less effective at the later stages of serial recall than listening and handwriting tasks. This could be due to a reduction in the efficiency of transforming the most recently presented items into a phonological code then storing and rehearsing them in memory before immediate recall begins. Conversely, we can see that words with an auditory input (i.e., the listening and
handwriting conditions) are being processed automatically as they are phonologically coded (Baddeley & Larsen, 2007; Haenggi & Perfetti, 1992). Further to this, the pattern of order errors indicates that the reading condition allowed efficient encoding of words (with no difference in order errors compared to listening). This suggests that the underlying processes involved in reading do not disrupt WM as much as a concurrent handwriting task. This also indicates that in this task there is no difference in encoding information while reading or listening, which may indicate that changes in performance in the reading condition are due other factors (e.g., the maintenance of words while reading).

Based on overall recall, the most cognitively complex task is handwriting, where there is the additional process of converting the phonological information to its written form and programming and performing the handwriting movements (Kellogg, 1996). The design of the experiment is such that the only difference between the listening and handwriting tasks was writing words as the participants listened to them. This takes up more of the limited WM resources, leaving less available for encoding and storage (Barrouillet & Camos, 2007; Chun, 2011). Previous research has indicated that the handwriting process utilises WM (Benton, Kraft, Glover, & Plake, 1984; Kellogg, 1996; McCutchen, 2000; Olive, 2004; Tse et al, 2014), which explains why handwriting places significantly more strain on WM than reading and listening.

The observed pattern of recall in the handwriting condition suggests some level of interference during the encoding, rehearsal, and/or maintenance of words while the words are being written. The rehearsal/maintenance of the first items presented is inhibited by the handwriting during encoding and recall. The ability to recall the most recently presented items is indistinguishable between the handwriting and listening conditions, possibly because the concurrent handwriting pauses once the last word has been presented. This could allow the participants directing their attention towards maintaining the most recently presented items before recall begins (Barrouillet & Camos, 2007).
The results in this experiment show that handwriting resulted in a reduction in recall and an increase in order errors compared to the reading and listening conditions. The increase in order errors implies that the words are not being encoded efficiently within the phonological loop while handwriting (Acheson & MacDonald, 2009), as resources are divided between processes (Barrouillet & Camos, 2007). This prevents items from being stored and retrieved at the correct serial position (Acheson & MacDonald, 2009). Conversely, no differences in order errors occurred between the listening and reading conditions, which corresponds to the main effect for recall in the repeated measures analysis. This reinforces that handwriting is a cognitively complex and demanding process that disrupts encoding and prevents accurate recall of to-be-remembered words, compared to reading and listening.

The increase in recall at serial position five and six in the handwriting condition is consistent with what is expected for serial recall of verbally presented stimuli (Hurlstone, Hitch, & Baddeley, 2014; Logie, Della Sala, Wynn, & Baddeley, 2000; Saito, Logie, Morita, & Law, 2008; Tan & Ward, 2008). I argue that the handwriting condition did not elicit poorer recall at these serial positions as the methodology allowed immediate recall. As shown in previous serial recall tasks of verbally presented stimuli (Pattamadilok, Lafontaine, Morais, & Kolinsky, 2010; Saito et al., 2008; Spurgeon, Ward, & Matthews, 2014), the recency effect is due to short term memory’s ability to hold those items relatively well and sustain them for immediate recall.

In light of this, the findings can be interpreted as follows. The handwriting pauses after the presentation of the final word, allowing attentional resources to be switched back to encoding and maintenance. The items can therefore be rehearsed/maintained much more efficiently. In contrast, while encoding each of the early words, the handwriting task continues as participants write down subsequent words, leading to a weaker memory trace for the earlier words. The memory trace for the most recently presented item is stronger as it remains activated in short term memory for immediate retrieval (Pattamadilok et al., 2010).
While this explanation is consistent with my results, further research will be required for confirmation. The novel effect of poor recall during the beginning of the serial position list (in the handwriting condition) is worth further investigation and may help explain the cognitive effects of handwriting on WM. However, this appears to be related to methodology in the present study where the words are written during recall, since this pattern changes with verbal recall (see later chapters). As such, further investigation of this is beyond the scope of my thesis.

Given that previous literature shows that handwriting relies on WM to produce written material, it was of importance to further investigate this interaction in terms of encoding, maintaining, and retrieving information that is written. The finding that handwriting interferes with WM processing is an interesting theoretical finding. What is more interesting, is where these differences occur. As outlined, there are differences across the serial positions between the three conditions, which shows that different mechanisms are being affected. As the differences in the handwriting condition occur during the primacy items, this suggests that there is a problem with encoding while writing, which was not evident in the reading and listening condition. This is of theoretical importance - as argued, handwriting is preventing the encoding of items, which prevents them from being maintained and retrieved. The optimal performance for the recency items is due to the phonological nature of the stimulus (i.e., the words were being listened to). This resulted in a stronger recency effect because items could be recalled immediately and were not subjected to interference from additional writing while encoding. This is also evident from the similar results between listening and writing for the final few items.
Conclusion

This experiment fills a void in the literature demonstrating that handwriting overloads WM more than reading and listening, leading to worse recall of concurrently presented words. This indicates that handwriting is more cognitively complex and places a greater strain on WM processes than reading and listening. The cognitive requirements associated with writing could be preventing attention from switching back to processing and maintaining items within WM (Barrouillet & Camos, 2007). The results suggest that a trade-off exists between task complexity, and retaining information in WM. That is, the more complex a task or the more difficult it is to perform by an individual, the fewer words are recalled in a concurrent verbal WM task. Furthermore, this has a different impact on earlier or later words in a list depending on the WM processes affected.

Experiment 3.1 has established that handwriting reduces verbal serial recall performance. However, the methodology used to recall words could explain the pattern of results found in the handwriting condition. As I identified, handwriting reduced WM performance, therefore by requiring participants to write down their responses this could be contributing to a further reduction in performance across all the DV’s. For example, if writing is detrimental to WM performance, asking participants to write down responses could be contributing to further reductions. To specifically address how handwriting interferes with WM during encoding the remaining experiments will require participant to verbally recall item lists.

In the following chapter I will investigate which mechanisms of handwriting contribute to the reduction in verbal serial recall performance. Experiment 3.1 extended previous literature by showing that handwriting reduces working performance during encoding when the two tasks are performed simultaneously. In the next chapter I will identify whether this reduction is due to the verbal component of handwriting (e.g., spelling), the complex motor movements, or both.
Chapter 4 – Investigating the lower level demands of writing: Handwriting movements interfere with verbal serial recall

Parts of this chapter has been adapted from the publication:

The study detailed in Chapter 3 identified that a simultaneous handwriting task reduces WM performance across a serial position curve. These generated the question of which component of handwriting (e.g., motor or phonological components) led to this reduction in performance. In the following experiments, I investigate this by specifically manipulating the different components of handwriting by looking at how writing like movements (pseudo-handwriting) independent of a phonological component might contribute to the interference of verbal WM performance. It does this by comparing the serial verbal recall when performing a pseudo-handwriting task to recall when just listening or performing a writing while listening task.

In the following experiments, some of the participants took part in more than one of the experiments. However, of the sample, only 3 or 4 participants participated in more than one experiments. Most participants were unique to each study and were recruited from undergraduate classes, across a period of 1-2 years.

4.1 Pseudo-Handwriting

The next three paragraphs are adapted from the literature review and are included to provide clarity and context to the chapter.

The interaction between WM and writing processes is complex and requires the sharing of a limited pool of cognitive resources (Kellogg, 1996). The performance of WM tasks and writing tasks is determined by the availability of those cognitive resources and how they are shared. This is to ensure efficient and legible writing while maintaining the active components of WM. When performing a writing task, WM is engaged automatically. This process cannot be inhibited, as it is a necessity to manage the initial demands of writing. The current study is primarily concerned with the lower levels of writing, namely, handwriting and spelling (Janssen, Braaksma, & Rijlaarsdam, 2010; Swanson & Berninger, 1996; Vanderberg
Handwriting and Pseudo-Handwriting

& Swanson, 2006). When I refer to handwriting, I am concerned with the motor requirements needed to produce letters and words, as well as ensuring the correct spatial sequence of letters (Berninger & Graham, 1998). Secondly, handwriting is also concerned with the verbal requirements needed to spell words and form legible sequences of letters. As noted above, writing has been investigated in regard to how it overloads and relies on WM, typically for generating large amounts of text (e.g., comprehension, composition). However, there is little research on how the lower level demands of handwriting contribute to a reduction in WM performance and further investigation is needed to understand how resources are shared between handwriting and WM during encoding and maintenance.

The TBRS model of WM (Barrouillet, Bernardin, & Camos, 2004; Barrouillet & Camos, 2007) gives insight into how resources are shared between WM and concurrent tasks. This model is concerned with the time-related decay of information when attention (the resource) is diverted away from the original focus of attention. The longer attention is captured elsewhere, the poorer the performance on the original process or task. The model assumes that the processing and maintenance of relevant information utilises a limited attentional resource, and that attention is rapidly switched between them. Additionally, it is assumed that a central bottleneck exists which only allows one cognitive process to occur at a time. When performing multiple cognitive tasks, the sharing/switching of that resource is automatic. If attention is diverted from the maintenance and processing of the memory item, then it is subject to decay. This increases the risk of items being forgotten and only by focussing attention back to processing and maintenance can the item be retrieved (Cowan, 1995, 2001, 2010). The longer that the item is not activated the more decay it is subject to and the harder it will be to re-activate when attention can be diverted back to maintenance and processing (Cowan, 1995; Oberauer, 2002). Therefore, it is suggested that any process that captures attention (such as handwriting) hinders the processing, maintenance, and retrieval of to-be-remembered items (Barrouillet & Camos, 2007).
Within the framework of handwriting and the TBRS model, it is plausible that performing a concurrent handwriting task while trying to process and maintain items within WM would capture attention and limit the availability of resources to switch back to process, maintain, and retrieve relevant items. Based on Kellogg’s (1996) model of WM in writing and recent work by Tse et al. (2014), it appears that handwriting requires WM processing, and places significant demands on attention, limiting the recall of relevant information (Bourdin & Fayol, 1994, 2002; Tindle & Longstaff, 2015). It is also well-established that attention is needed to complete the verbal and spatial components of handwriting. However, it has not been established which component of the handwriting process is responsible for the decrease in WM performance. In other words, if there is a reduction in immediate verbal serial recall, is it due to the complex motor task of handwriting, or due to the verbal component of handwriting, or both?

Previous literature and Experiment 3.1 has only investigated the holistic aspects of handwriting, and only its detrimental effect when handwriting is performed during retrieval (Bourdin & Fayol, 1994, 2002). However, we do not have a grasp on how the different components of handwriting are interfering with WM processes. This chapter will investigate if there is a decrease in verbal serial recall performance when a handwriting task is performed during the processing and maintenance stage of WM while listening to the words to be recalled. The handwriting task that participants complete will require them to listen to words and write them down verbatim as they are hearing them.

I will also investigate whether performing a pseudo-handwriting task will reduce the demand for attentional resources and increase performance on recall compared to handwriting. If there is no difference in performance between the handwriting and pseudo-handwriting tasks, this will indicate that the verbal component of handwriting does not capture attentional resources. To test this, I will implement a pseudo-handwriting condition that resembles the motor component of handwriting without the need to focus on the spelling
of words. The pseudo-handwriting condition will require participants to write cursive “el” combinations, which is a well-established paradigm for testing handwriting movement fluency (e.g., Bryant, Rintala, Lai, & Protas, 2010; Caligiuri, Teulings, Dean, Niculescu, & Lohr, 2011; Dooijes, 1983; Meulenbroek & van Galen, 1988; Slavin, Phillips, & Bradshaw, 1996; Smits et al., 2014; Teulings, 1996; Teulings, Contreras-Vidal, Stelmach, & Adler, 1997; Tucha & Lange, 2001, 2004, 2005; Tucha, Mecklinger, Walitza, & Lange, 2006; Tucha, Walitza, et al., 2006). The movements that are produced with cursive “el” combinations are reflective of complex fine motor movements produced during handwriting (Teulings, 1996). As such, it is a valid and reliable measure of how we control the motor component of handwriting. Therefore, there are two handwriting conditions – Firstly, a condition that requires two functions of handwriting (e.g. the motor and verbal demands). Secondly, a condition that only requires one lower level handwriting function (e.g. the motor demands).

Based on previous verbal serial recall paradigms it is expected that all of the conditions will elicit strong primacy and recency effects, with significant drops in performance in the middle serial positions (serial positions 3-5; Allen & Hulme, 2006; Logie, Della Sala, Wynn, & Baddeley, 2000; Pattamadilok et al., 2010). I expect, based on the findings from chapter 3 and those from handwriting and WM studies (e.g., Bourdin & Fayol, 1994, 2002), that overall recall will be significantly different between all three conditions. With recall being the best in the listening condition (no additional demands on resources), moderate in the pseudo-handwriting condition (addition of motor demands), and poorest in the handwriting condition (addition of motor and verbal demands).

Furthermore, I will investigate at which serial positions the three conditions diverge significantly from one another. Based on both the TBRS model and Cowan’s (2001, 2010) conceptualisation of a maximum of three to five chunks of information that can be actively maintained within the focus of attention, I expect that the deterioration in recall will be
greatest around the mid (i.e. third to fifth) serial positions. At the primacy and recency items, resources are at their maximum availability and can be shared between the multiple tasks efficiently and so it is predicted there will be no differences in recall between conditions. However, as we move across the serial position, the resources must be shared/switched between an increasing number of cognitive processes. By the time we reach the middle serial positions, attention must be shared/switched between the verbal and motor components in the handwriting task, and the motor component of the pseudo-handwriting task, in addition to the processing and maintenance of the words at each serial position. It is hypothesised that the increased sharing/switching of resources between multiple cognitive processes will result in a further reduction in recall at the middle serial positions. With recall being the best in the listening condition, moderate in the pseudo-handwriting condition, and worst in the handwriting condition.

Method

Participants

The experiment included fifteen voluntaries (Females, n = 8; Males, n = 7) participants from the university and general public. The mean age of participants was 38.73 (SD = 13.42) most participants were studying at university (n = 13) while others had completed non-university tertiary studies (n = 2). All participants were required to speak English as their first language and have normal to corrected to normal vision and hearing. All participants provided informed consent. The Southern Cross University Human Research Ethics Committee approved this study.

Design
The conditions in this experiment were listening, handwriting (i.e. listening while writing down the words), and pseudo-handwriting (listening while drawing combinations of small and large loops) and serial position with six levels (positions one to six).

Apparatus

The shapes used in the experiment were small and large loops that were designed using combinations of the letters ‘el’ in Jellico Saint-Andrew's Queen Font as seen in Figure 4.1. Different combinations were used for each trial. For example, ‘elele’ was used in one trial and ‘ell’ for another, and so on. The small loops had a stroke size of 5 mm and large loops had a stroke size 11 mm, which is within the range of typical handwriting stroke sizes (e.g. Caligiuri, Teulings, Dean, Niculescu, & Lohr, 2011; Contreras-Vidal, Teulings, & Stelmach, 1998; Rosenblum, Samuel, Zlotnik, Erikh, & Schlesinger, 2013; Smits et al., 2014; Teulings, 1996; Teulings & Stelmach, 1991; Tucha et al., 2006).

![elele](image)

Figure 4.1. A sample of the combination of loops used in the pseudo-handwriting condition, Jellyka Saint Andrew's font.

Procedure

Participants completed the experiment individually. Upon entering the room, participants were greeted by the experimenter and asked to take a seat in the cubicle where the experiment took place. Participants were asked to read the information sheet that outlined the purpose of the experiment, what was required of them as well as instructing them of their
Handwriting and Pseudo-Handwriting

rights to participate and withdraw. Participants then completed a consent form, which was signed and dated.

Once this was completed, the experimenter instructed the participants that they were going to complete a WM task. Participants were told that they are going to complete a serial verbal recall task; this required them to listen to a series of words before recalling them aloud. They were given the example, if you hear the words “dog, cat, bat, elephant, rabbit, spider” then you are to recall them aloud in the same order you just heard. If you do not remember a word in a certain position, you are to say the word ‘blank’. For example, if you do not remember the third word, you are to say “dog, cat, blank, elephant, rabbit, spider”. Participants were told that each list had exactly 6 words and that there were 15 lists in each condition. This procedure for recall was the same for all conditions.

The participants were then instructed on how the program worked and what they needed to do during the experiment. Firstly, the participants were asked to place the headphones on and then a practice example was opened on MovAlyzeR and the experimenter walked the participant through the procedure. Participants were shown the ‘START’ icon and told that throughout the experiment to start a new list they must move the stylus through the start icon. After doing this, they would begin to hear a list of words.

When participants were completing the listening task, they were instructed to move the stylus through the ‘START’ icon to start the list of words, they were asked to focus on an ‘X’ that appeared on the centre of the screen. During the listening condition participant did not complete a concurrent task but only heard the words. Once the list ended, the word ‘RECALL’ appeared on the screen and participants were instructed that this was where they had to recall the words in the order they were presented. Participants practiced the listening task until they were comfortable and the experimenter was comfortable with their ability to use the program. At this point, the experimenter started the listening condition and left the
room, participants were asked to contact the experimenter once the condition had been completed.

When completing the handwriting condition, participants were instructed to move the stylus through the ‘START’ icon to start the list of words. They were then instructed to begin writing down the words they were listening to during the presentation of the first word. Participants were told to write in their natural handwriting and attempt to write down each word even if they were unsure of the correct spelling. It was emphasised that they must attempt to write down each word. Participants continued writing until they heard a beep at the end of the list; this was to prompt them to stop writing. At this point, the participants’ writing disappeared from the screen and ‘RECALL’ appeared on the centre of the screen. Participants then practiced the handwriting task until they were comfortable and the experimenter was comfortable with their ability to use the program. At this point, the experimenter started the handwriting condition and left the room, participants were asked to contact the experimenter once the condition had been completed.

When completing the pseudo-handwriting task, the same protocol was followed. After pressing the ‘START’ icon participants were then instructed to begin to draw the stimuli that appeared on the screen concurrently with the presentation of the word lists. Participants were told to continuously draw the loop combinations as quickly and accurately as possible, without lifting the pen until they heard a beep at the end of the list; this was to prompt them to stop moving. So, if the pattern was ‘eell’, they would draw ‘eelleelleell…’ until they heard the beep. At this point, the participants’ pseudo-handwriting disappeared from the screen and ‘RECALL’ appeared on the centre of the screen. Participants then practiced the pseudo-handwriting task until they were comfortable and the experimenter was comfortable with their ability to use the program. At this point, the experimenter started the pseudo-handwriting condition and left the room, participants were asked to contact the experimenter once the condition had been completed.
The order the participants completed conditions was counterbalanced. The instructions were given before the beginning of each condition and not at the start of the experiment. This was to limit confusion between tasks and to ensure that participants were aware of the task they were completing throughout the experiment.

Results

Recall was measured as the proportion of words recalled correctly at each serial position. Shapiro–Wilks analysis revealed assumptions of normality were violated for the listening ($p = .024$), pseudo-handwriting ($p = .02$), and handwriting ($p = .016$) conditions. Additionally, $F_{max}$ was 3.07 indicating homogeneity of variance was met. Mauchly’s test showed that sphericity was met for Condition, $\chi^2 (2) = 5.07, p = .079$, and the Condition × Serial Position Interaction, $\chi^2 (54) = 73.67, p = .069$. Sphericity was violated for serial position, the degrees of freedom were adjusted using Huynh–Feldt ($\varepsilon$) corrections (Allen & Bennett, 2010; Tabachnick & Fidell, 2007), $\chi^2 (14) = 51.29, p < .001, \varepsilon = .66$. Figure 4.2 summarises the mean proportion of words recalled in the listening condition, the handwriting condition, and the pseudo-handwriting condition.
The repeated measures analysis of variance (ANOVA) revealed a significant main effect for Condition, $F(2, 28) = 10.20, p < .001, \eta^2_p = .42$, showing a difference in recall between the listening, pseudo-handwriting, and handwriting conditions. The mean number of words recalled per list for the listening condition was 3.12 ($SD = .98$), 2.51 ($SD = .91$) for the pseudo-handwriting condition, and 2.61 ($SD = .97$) for the handwriting condition. This shows that the mean number of words recalled was between 2.5 and 3 words per list for all of the conditions. Bonferroni post hoc comparisons revealed that participants recalled significantly more words overall in the listening condition compared to the pseudo-handwriting condition [$M_{Diff} = .10$, Bonferroni 95% CI: .06–.15], and the handwriting condition [$M_{Diff} = .08$, Bonferroni 95% CI: .02–.15]. There was no significant mean difference between the
proportion of words recalled in the handwriting and pseudo-handwriting conditions \( [M_{\text{Diff}} = .02, \text{Bonferroni 95\% CI: } -.06--.09] \).

There was a significant effect for serial position, \( F (1.92, 26.88) = 15.49, p < .001, \eta^2_p = .53 \), and the Condition × Serial Position interaction, \( F (10, 140) = 3.23, p = .001, \eta^2_p = .19 \).

An analysis of simple effects was conducted using Bonferroni adjusted linear contrasts to determine if differences in recall occurred between conditions at individual serial positions. The results of the F-tests are shown in Table 4.1. Firstly, there was no significant difference in the proportion of words recalled correctly between the pseudo-handwriting and handwriting conditions at any serial position. However, there were consistent differences between the listening condition compared to the handwriting and pseudo-handwriting conditions. The mean proportion of words recalled was highest for listening at serial positions one to four. The linear contrasts revealed that significantly more words were recalled correctly in the listening condition compared to the handwriting and the pseudo-handwriting conditions at these serial positions. Additionally, at serial position five, significantly fewer words were recalled in the listening condition compared to the handwriting condition. No significant differences occurred between any of the conditions at serial position six.

Order errors were analysed as the proportion of order errors in each condition. A repeated measures ANOVA revealed no significant difference between the proportion of order errors made in each condition, \( F (2, 28) = .65, p = .52, \eta^2_p = .05 \).
Table 4.1
Linear Contrast Results for Differences between Conditions at Serial Positions (SP) 1 to 6.

<table>
<thead>
<tr>
<th>SP</th>
<th>Variables</th>
<th>df</th>
<th>F</th>
<th>p</th>
<th>95% CI [Lower-Upper]</th>
</tr>
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<td>L &gt; H</td>
<td>1, 14</td>
<td>7.78</td>
<td>.015*</td>
<td>.00, .26</td>
</tr>
<tr>
<td></td>
<td>L &gt; PH</td>
<td>1, 14</td>
<td>6.82</td>
<td>.021*</td>
<td>-.01, .27</td>
</tr>
<tr>
<td></td>
<td>PH = H</td>
<td>1, 14</td>
<td>0.002</td>
<td>.965</td>
<td>-.19, .2</td>
</tr>
<tr>
<td>2</td>
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<td>1, 14</td>
<td>5.37</td>
<td>.037*</td>
<td>-.02, .30</td>
</tr>
<tr>
<td></td>
<td>L &gt; PH</td>
<td>1, 14</td>
<td>19.85</td>
<td>&lt;.001**</td>
<td>.05, .36</td>
</tr>
<tr>
<td></td>
<td>PH = H</td>
<td>1, 14</td>
<td>.73</td>
<td>.407</td>
<td>-.26, -.14</td>
</tr>
<tr>
<td>3</td>
<td>L &gt; H</td>
<td>1, 14</td>
<td>8.99</td>
<td>.01*</td>
<td>.02, .36</td>
</tr>
<tr>
<td></td>
<td>L &gt; PH</td>
<td>1, 14</td>
<td>10.78</td>
<td>.005*</td>
<td>0, .25</td>
</tr>
<tr>
<td></td>
<td>PH = H</td>
<td>1, 14</td>
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<td>.391</td>
<td>-.11, .22</td>
</tr>
<tr>
<td>4</td>
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<td>.05, .30</td>
</tr>
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<td></td>
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<td>13.76</td>
<td>.002*</td>
<td>.05, .31</td>
</tr>
<tr>
<td></td>
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<td>.01</td>
<td>.922</td>
<td>-.15, .14</td>
</tr>
<tr>
<td>5</td>
<td>L &lt; H</td>
<td>1, 14</td>
<td>4.78</td>
<td>.046*</td>
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</tr>
<tr>
<td></td>
<td>L = PH</td>
<td>1, 14</td>
<td>.01</td>
<td>.935</td>
<td>-.09, .09</td>
</tr>
<tr>
<td></td>
<td>PH = H</td>
<td>1, 14</td>
<td>3.37</td>
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<td>-.17, .03</td>
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<td>6</td>
<td>L = H</td>
<td>1, 14</td>
<td>1.15</td>
<td>.302</td>
<td>-.19, .08</td>
</tr>
<tr>
<td></td>
<td>L = PH</td>
<td>1, 14</td>
<td>.73</td>
<td>.407</td>
<td>-.15, .08</td>
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<td></td>
<td>PH = H</td>
<td>1, 14</td>
<td>.104</td>
<td>.752</td>
<td>-.17, .13</td>
</tr>
</tbody>
</table>

Note: L – Listening condition; PH – Pseudo-handwriting condition; H – Handwriting condition
* Significant effect at α = .05
** Significant effect at α = .001

Discussion

The results supported the hypothesis and were consistent with previous works indicating that overall recall would be best during the listening task. Consistent with my predictions, there were significant differences in the mid-serial positions, but contrary to expectations, there were also differences early on. This suggests that the secondary tasks are capturing resources from the beginning of the primacy phase as well as the maintenance phase. Also, contrary to expectations, the pseudo-handwriting condition displayed a similar pattern of recall to the handwriting condition. It appears both handwriting and pseudo-
handwriting conditions are reducing WM performance to a similar extent. This suggests that it is the motor component of the tasks that is impacting on performance with little contribution from the verbal aspect of the handwriting task. Alternatively, it is possible that this unexpected result is due to the stimuli used in the pseudo-handwriting condition. When transcribing the loop combinations participants may be sub-vocalising the large and small loops as the letters “e” and “l”. If so, this would add a verbal component similar to the handwriting task. To further establish whether handwriting-like movements, independent of a verbal component needed to spell is reducing WM performance. In order to control for this, a subsequent experiment was conducted to address the possible confound in the pseudo-handwriting condition in experiment 4.1.

4.2 Inverted Pseudo-Handwriting

The following experiment is a replication of experiment 4.1 with some modifications to the stimuli and apparatus to accommodate the changes within the pseudo-handwriting condition. The design and procedure were almost identical to experiment 4.1. There were two main changes to the experiment, firstly, the device participants wrote on was changed. In experiment 4.1, participants wrote/drew on an external Wacom tablet attached to a PC, where they were transcribing their movements and receiving visual feedback on separate spatial domains. That is, participants wrote on the tablet but were looking at the computer screen to gain feedback. Although this methodology has been used in numerous handwriting studies (e.g. Bryant et al., 2010; Caligiuri et al., 2011; Dooijes, 1983; Teulings, 1996; Teulings et al., 1997; Tucha et al., 2006; Tucha & Lange, 2001, 2004, 2005), it could be argued that this method does not fully resemble an actual writing environment. In experiment 4.2, a Microsoft surface pro with MovAlyzeR was used to collect the movement data. This enabled participant
to write on the tablet screen and gain visual feedback on the same surface they were writing on. This replicates a more natural writing space.

The second change was to the pseudo-handwriting stimuli. Instead of transcribing loop combinations displayed on a screen, participants traced over inverted loops that were displayed on the tablet screen. This was done to remove the possible confound of the verbal component needed to transcribe the letter loops that may have been present in experiment 4.1. Secondly, the aim of the research was to assess if handwriting without the need to spell would interfere with WM processes. By implementing the tracing aspect, we specifically manipulate handwriting-like movements and remove some of the demand of the planning component of writing. This method enables a greater control over the stimuli and gives participants a setting or device corresponding closer to normal writing conditions. If the results of experiment 4.1 were due to the existence of a verbal component in the upright “el” patterns then I would hypothesise that in this experiment there would be greater recall for the listening condition, followed by the pseudo-handwriting condition, with worst recall for the handwriting condition. However, if the reduction in performance was primarily due to the motor component of the handwriting condition, I would expect similar results to experiment 4.1, with best performance for the listening condition and similar performance for the handwriting and pseudo-handwriting tasks.

**Method**

**Participants**

The experiment included 20 voluntary (Females, $n = 9$; Males, $n = 11$) participants from the university and general public. The mean age of participants was 35.15 ($SD = 11.47$); most participants were studying at university ($n = 17$) while others had also completed non-university tertiary studies ($n = 3$), that is, participants had a minimum of 12 years education. All participants were required to speak English as their first language and have normal to
corrected to normal vision and hearing. All participants provided informed consent. The Southern Cross University Human Research Ethics Committee approved this study.

**Apparatus**

The experiment was conducted in a lab set-up with a Microsoft surface pro and stylus to display the stimuli and record the movements of participants. MovAlyzeR displayed the movements on the tablet screen in real time and recorded the pen movements. The participants were given a pair of headphones to listen to a pre-recorded list of words spoken by the researcher, also presented via MovAlyzeR. The same words obtained in experiment 4.1 were used however new word lists were designed and counterbalanced. The shapes used in the pseudo-handwriting condition were the same as experiment 4.1 but were inverted; different combinations of loops were used for each trial. The inverted loops were superimposed on the tablet screen for the participant to trace over. An example of the inverted loops can be seen in Figure 4.3.

![Example of inverted loops](image)

Figure 4.3. A sample of the combination of inverted loops used in the pseudo-handwriting condition, Jellyka Saint Andrew’s font.

**Procedure**

The pseudo-handwriting condition differed to experiment 4.1 by asking participants to continuously trace over combinations of large and small inverted loops while listening to the word lists. Participants did this by pseudo-handwriting on the computer/tablet screen. The handwriting condition differed to experiment 4.1 as participants could now write directly on
the tablet screen rather than indirectly through the Wacom tablet. All other aspects of the
experiment were identical to experiment 4.1.

**Results**

Recall was measured as the proportion of words recalled correctly at each serial
position. Shapiro–Wilks analysis revealed assumptions of normality were met for the
listening \((p = .72)\), pseudo-handwriting \((p = .83)\), and handwriting \((p = .25)\) conditions. Additionally, \(F_{max}\) was 4.66 indicating homogeneity of variance was met. Mauchly’s test showed that sphericity was met for Condition, \(\chi^2 (2) = .32, p = .852\), but was violated for Serial Position, \(\chi^2 (14) = 5.99, p < .001, \varepsilon = .50\), and the Condition \(\times\) Serial Position interaction, \(\chi^2 (54) = 89.27, p = .003, \varepsilon = .60\), the degrees of freedom were adjusted using Huynh–Feldt \((\varepsilon)\) corrections. Figure 4.4 summarises the mean words recalled in the listening
condition, the handwriting condition, and the pseudo-handwriting condition.
The repeated measures ANOVA revealed a significant main effect for experimental condition, $F(2, 38) = 9.82, p < .001, \eta_p^2 = .34$. The mean number of words recalled per list for the listening condition was 3.04 ($SD = 1.08$), 2.56 ($SD = .87$) for the pseudo-handwriting condition, and 2.58 ($SD = .90$) for the handwriting condition. This shows that the mean number of words recalled was around 2.5–3 words per list for all of the conditions. A series of Bonferroni adjusted pairwise comparisons revealed that participants recalled significantly more words overall in the listening condition compared to the pseudo-handwriting condition [$MDiff = .081$, Bonferroni 95% CI: .02–.14], and the handwriting condition [$MDiff = .086$, Bonferroni 95% CI: .30–.15]. There was no significant mean difference between the proportion of words recalled in the pseudo-handwriting and handwriting conditions. A comparison of overall performance for the three tasks in experiments 4.1 and 4.2 can be seen.
in Figure 4.5. This shows a remarkably consistent pattern across the two experiments and in particular the two different pseudo-handwriting tasks.

![Figure 4.5. Mean overall word recall as a proportion of correct responses for the listening, pseudo-handwriting, and handwriting conditions in experiments 4.1 and 4.2.](image)

There was also a significant main effect for Serial Position, $F(2.48, 47.13) = 3.45, p < .001, \eta_p^2 = .57$, and a significant Condition $\times$ Serial Position interaction with a moderate effect size, $F(6.04, 114.73) = 2.31, p = .038, \eta_p^2 = .11$. An analysis of simple effects was conducted using linear contrasts to determine if differences in recall occurred between conditions at individual serial positions, the results of the F-tests are shown in Table 4.2. The linear contrasts showed that, similar to experiment 4.1, there were no differences between handwriting and pseudo-handwriting at serial positions two to six. Although there was a difference at position one with more words recalled in the pseudo-handwriting condition
compared to the writing condition. The mean proportion recall was highest for listening at serial positions one to five, with significant differences at position one and two between listening and handwriting, and serial positions four and five between listening and pseudo-handwriting. There was no significant difference between conditions at position six.

Table 4.2
Linear Contrast Results for Differences between Conditions at Serial Positions (SP) 1 to 6.

<table>
<thead>
<tr>
<th>SP</th>
<th>Variables</th>
<th>df</th>
<th>F</th>
<th>p</th>
<th>95% CI[Lower-Upper]</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>L &gt; H</td>
<td>1, 19</td>
<td>12.44</td>
<td>.002*</td>
<td>.05 - .36</td>
</tr>
<tr>
<td></td>
<td>L = PH</td>
<td>1, 19</td>
<td>2.10</td>
<td>.164</td>
<td>-.05 - .16</td>
</tr>
<tr>
<td></td>
<td>PH &gt; H</td>
<td>1, 19</td>
<td>6.10</td>
<td>.023*</td>
<td>-.01 - .30</td>
</tr>
<tr>
<td>2</td>
<td>L &gt; H</td>
<td>1, 19</td>
<td>13.25</td>
<td>.002*</td>
<td>.04 - .26</td>
</tr>
<tr>
<td></td>
<td>L = PH</td>
<td>1, 19</td>
<td>3.27</td>
<td>.086</td>
<td>-.04 - .21</td>
</tr>
<tr>
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<td>-.110 - .24</td>
</tr>
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<td>4.17</td>
<td>.055</td>
<td>-.03 - .21</td>
</tr>
<tr>
<td></td>
<td>L = PH</td>
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<td>1.33</td>
<td>.263</td>
<td>-.07 - .12</td>
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<td></td>
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<td>.497</td>
<td>-.10 - .18</td>
</tr>
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<td>4</td>
<td>L = H</td>
<td>1, 19</td>
<td>3.45</td>
<td>.079</td>
<td>-.05 - .26</td>
</tr>
<tr>
<td></td>
<td>L &gt; PH</td>
<td>1, 19</td>
<td>6.07</td>
<td>.023*</td>
<td>-.01 - .27</td>
</tr>
<tr>
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<td>.652</td>
<td>-.16 - .11</td>
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<td>0.10</td>
<td>.755</td>
<td>-.13 - .17</td>
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<td></td>
<td>L &gt; PH</td>
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<td>5.81</td>
<td>.026*</td>
<td>-.01 - .22</td>
</tr>
<tr>
<td></td>
<td>PH = H</td>
<td>1, 19</td>
<td>3.21</td>
<td>.089</td>
<td>-.22 - .04</td>
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<td>1.10</td>
<td>.307</td>
<td>-.19 - .08</td>
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<td>PH = H</td>
<td>1, 19</td>
<td>2.66</td>
<td>.119</td>
<td>-.25 - .06</td>
</tr>
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</table>

*Significant effect at α = .05
**Significant effect at α = .001

Order errors were analysed as the proportion of order errors in each condition, sphericity was met. A repeated measures ANOVA revealed a significant difference between the proportion of order errors made in each condition, $F(2, 38) = 4.78, p = .014, \eta^2_p = .2$. Bonferroni adjusted pairwise comparisons revealed that the proportion of order errors were significantly higher for the pseudo-handwriting condition compared to the listening condition $[\text{MDiff} = .07, \text{Bonferroni 95\% CI: .02-.12}]$. No other comparisons revealed a significant difference in the proportion of order errors.
Discussion

The results supported the hypothesis and were consistent with experiment 4.1 and previous works indicating that overall recall would be greatest during the listening task compared to pseudo-handwriting and handwriting. Consistent with experiment 4.1, overall recall was no different between the pseudo-handwriting and handwriting conditions. There were also subtle variations between conditions across the serial positions. As found above, there was no difference in the proportion of words recalled between the handwriting and pseudo-handwriting conditions at serial positions two to six. However, there was a difference at serial position one, with more words recalled in the pseudo-handwriting condition. As in experiment 4.1, the proportion of words recalled was higher for the listening condition at serial positions one to five. Again, there were subtle variations, with the difference between listening and handwriting greatest at positions one and two, and between listening and pseudo-handwriting at positions four and five. The pattern of results across the experiments suggests that there may have been some phonological component in the upright “el” patterns in experiment 4.1, but even when this is removed, the dominant effect of the motor component is still apparent. The verbal component of handwriting could be having some small additional effect on processing (particularly in the primacy phase), but not to the extent that was expected. This may reflect some initial processing demands associated with the verbal component of handwriting.

Furthermore, the results of experiment 4.1 and 4.2 suggest that the motor component in the pseudo-handwriting task may be having a greater effect than first thought. Both tasks are disrupting WM processes to a similar extent (with only minor differences occurring in the pattern across serial positions), regardless of the need to spell in the handwriting condition. This indicates there is little additional effect of the verbal component of handwriting. The similarity between the results of experiment 4.1 and 4.2 also suggest that the changing of devices (from PC to tablet) did not have an effect on recall. I would suggest that either device would be appropriate to use for these types of tasks.
4.3 General Discussion

From experiment 4.1 and 4.2 we can infer that both handwriting and pseudo-handwriting movements significantly reduce overall recall performance compared to just listening, and that they do not differ significantly from one another. This is despite the task demands in the handwriting condition such as the need to spell words. The consistency between experiment 4.1 and 4.2 shows a robust effect of fine motor movements on WM performance. Therefore, while there were some subtle differences in the processes (as revealed by the serial position analysis), the verbal component of handwriting did not appear to capture resources for any considerable additional amount of time that would further limit the switching of resources back to WM processing and storage. From this, I can conclude that attention is captured for relatively equal periods of time for a task that requires two functions of handwriting (the motor and verbal demands) compared to a task that requires one function of handwriting (the motor demands). I argue that this indicates that there is little additional demand associated with processing the verbal component of handwriting and that the majority of the decrease in memory performance is due to attention being captured by the complex motor movements of handwriting. Based on the findings I can assume that processes associated with the motor component of handwriting are largely responsible for the reduction of performance on a concurrent verbal WM task.

The results established that the handwriting and pseudo-handwriting conditions differed significantly in recall compared to the listening condition, which was expected. What is more interesting is that I only found subtle differences in recall between the handwriting condition and the pseudo-handwriting condition at individual serial positions, despite there being an additional verbal component (e.g. of spelling) in the handwriting condition. This was contrary to what was expected. It was hypothesised that in terms of the TBRS model, that the
additional verbal component in the handwriting condition would capture attention for a relatively longer period and further limit the availability of attentional resources for processing and maintenance. That is, in the pseudo-handwriting condition attention would be captured to produce the fine motor movements for tracing/writing the large and small loops. In the handwriting condition, attention would be captured by the handwriting movements to complete the different letter shapes and in addition, attention would also be captured to process the verbal component of handwriting. This result indicates that this did not occur, at least to the extent that was expected. There were no differences between handwriting and pseudo-handwriting in experiment 4.1 and the only significant difference between them in experiment 4.2 was at serial position one. Within the context of the TBRS model (Barrouillet & Camos, 2007), it would appear that the verbal component of handwriting does not capture attentional resources for sustained periods of time to complete. From this, I can infer that the reduction in recall between the handwriting and pseudo-handwriting condition compared to the listening condition is largely due to the motor component of handwriting with little to no additional reduction in performance that is due to the verbal component of handwriting.

Across the serial positions, I have found typical primacy and recency effects. At these positions, the limited pool of resources is at its maximum availability and can be switched between the multiple tasks efficiently. As we move across the serial position, attention is captured by an increasing number of cognitive processes and the availability of resources diminishes. In terms of the TBRS model (Barrouillet et al., 2004; Barrouillet & Camos, 2007), when attentional resources are rapidly switched between an increasing number of cognitive processes (e.g. processing and maintaining words at serial position one, two, three, etc..) we begin to see a decrease in recall performance. This was demonstrated within all three conditions in each experiment.

Further to this, in experiment 4.1 and 4.2 the differences in recall between listening and the handwriting/pseudo-handwriting conditions typically occurred during the early
Handwriting and Pseudo-Handwriting

middle serial positions. This can be interpreted in the context of Cowan’s (1995, 2001, 2005) model and the TBRS model (Barrouillet et al., 2004; Barrouillet & Camos, 2007) and the different processes and demands involved across serial positions. The models suggest that resources are at their limit around three to five items, so when performing an additional handwriting or pseudo-handwriting task we find further declines in recall. This is because there is a reduction in the availability of resources when attention is captured by the motor components of handwriting or pseudo-handwriting tasks while concurrently attempting to process/encode and maintain the words at each serial position. Consequently, when a handwriting task is completed concurrently, some of the attention is automatically captured to plan, execute, and monitor the motor movements. The addition of the handwriting/pseudo-handwriting tasks further reduces the ability to switch resources back to the processing and maintenance of words in WM. This effect appears to occur from serial position one and is particularly noticeable during the early to middle serial positions when available resources are at their limit.

The findings show a robust effect of handwriting in the context of the TBRS model. This model is concerned with the time-related decay of information when attention (the resource) is diverted away from the focus of attention. The longer it is captured elsewhere, the poorer the performance. The findings suggest that the bulk of resources are captured by the complex motor movements of handwriting for long periods (as demonstrated in the pseudo-handwriting task).

In addition to this, handwriting only disrupted WM processes significantly more than pseudo-handwriting at serial position one in experiment 4.2. This could indicate that there was some verbal component to the upright “el” pattern in experiment 4.1. If this is the case, it would appear that the initial verbal demands of handwriting disrupt processing and maintenance in addition to the disruption of the motor movements, but only for the first word of each list. This was not the case for the rest of the results where there was no difference
between pseudo-handwriting and handwriting. Therefore, the verbal component of handwriting does not seem to capture attention for longer periods compared to the pseudo-handwriting condition. The processes involved in spelling do not appear to capture attention for relatively longer periods to the handwriting movements. This implies that the handwriting movements mainly account for the disruptive capturing of resources for a longer time. This places constraint on the time that resources can be diverted back to processing and maintenance. I argue that the planning and executing movements needed to produce the letters (or letter-like shapes) capture attention for lengthy periods and prevent resources from switching back to processing and maintenance. This is reflected in the lack of differences in the overall proportion of words recalled between the two conditions, both in experiment 4.1 and 4.2.

While this finding is interesting, further research is needed to establish why additional resources were not captured by the verbal component of handwriting. While this is outside the scope of my thesis, I will provide the following as a possible explanation. In the context of Kellogg’s (1996) WM in writing model; before planning to write, words are held within WM to aid in the planning process (Ellis, 1982; Graham et al., 2000; Teulings, 1996; Tse et al., 2014). It could be that when performing a handwriting task simultaneously with a verbal WM task that the initial processing of the word (when it is heard) in WM acts as a central resource for that item. This would allow WM to reduce the resources that are needed for processing the word for memory storage, and processing the word for handwriting. For example, when the word is heard it is processed in verbal WM and once the word has entered WM the phonetics of that word are established and maintained (Baddeley, 2000, 2012). After the initial verbal processing, the word can then be rehearsed in WM for retrieval while simultaneously activating the motor component of WM to plan, execute, and monitor the written output. In other words, when executing the written output, the verbal processing occurs when the word is initially heard and utilised for both rehearsal and planning to write. This hypothesis needs
to be tested further, but could explain why the difference in recall between the handwriting and pseudo-handwriting condition only occurred at serial position one. This hypothesis could lend additional support to the findings by further isolating the effect of handwriting movements while explaining why there is little additional variance due to the verbal component of handwriting.

There are possible alternative explanations why there was no difference between the handwriting and pseudo-handwriting conditions. In both the below alternative explanations, there is a proposed mechanism that improves performance in a way that could counteract the detrimental effect of writing compared to pseudo-writing. Firstly, the generation effect, which is related to levels of processing theory of Craik and Lockhart (1972), explains that being actively involved in the production of verbal information seems to aid in remembering items more efficiently (Meulenbroek & van Galen, 1988; Slamecka & Graf, 1978; Taconnat & Isingrini, 2004). This is due to the deeper processing of the items. However, in the context of the levels of processing theory (Craik, 2002) and the generation effect, shallow processing involves processing word sounds, identifying letters, and the visual characteristics of a word (Craik & Tulving, 1975; Mandler, 2002; Slamecka & Graf, 1978). In the handwriting task in this experiment, participants were only concerned with those superficial aspects of the words, suggesting that only a shallow level of processing was achieved.

Secondly, the doodling effect was identified by Andrade (2007). Participants were required to shade/colour shapes while listening to a telephone call. It was found that that recall of specific details of a conversation was better when the participants completed an irrelevant doodling task while listening to a telephone call. It could be argued that the pseudo-handwriting task could contribute to an increase in recall similar to that found in the doodling effect. However, the pseudo-handwriting task in the current study consisted of copying and tracing loop shapes (e.g. combinations of “el”). This required constrained fine motor movements in contrast to the simple, unconstrained movements needed to shade shapes in the
doodling effect (Andrade, 2007). As such, a higher level of fine motor control is required to produce the “el” combinations, which limits the possibility of the results being due to the doodling effect. Therefore, I argue that the handwriting-like movement did have detrimental effect on overall recall and across the serial position curve.

The results of the study have supported previous findings on the complex nature of handwriting (Bourdin & Fayol, 1994, 2002) indicating WM performance is affected when asked to write down words while listening to them. Further to this, the research suggests that when attention is captured to produce complex handwriting movements it prevents resources from switching back to process, maintain, and retrieve items in WM (Barrouillet et al., 2004; Barrouillet & Camos, 2007). More importantly, I have successfully dissected the verbal and motor components of the handwriting processes. I have uniquely identified that the movements needed to produce legible and fluent handwriting are predominantly responsible for the interference in WM performance. In the broader context of writing (e.g. note-taking), the results support the idea that note-taking is a costly and exacting task that places significant demands on WM resources during dual and triple task procedures (Barbier, Piolat, Roussey, & Raby, 2008; Piolat, Barbier, & Roussey, 2008; Piolat, Olive, & Kellogg, 2005). Specifically, Piolat et al. (2005) reached similar conclusions to my findings, determining that the time needed to process note-taking impacted WM performance, though they did not investigate the verbal and motor components of handwriting.

So far, my experiments have established that both handwriting and handwriting-like movements disrupt WM performance compared to listening. I have speculated that this is due to the demanding nature of handwriting (and pseudo-handwriting) and the diverting of resources away from WM. However, I have not identified if there is also a decrease in handwriting performance when completed simultaneously with a WM task. That is, I do not know to what extent the resources are shared between the tasks. Furthermore, I am yet to provide evidence that supports the idea that there is a relationship between kinematic
measures of handwriting and WM when the tasks are performed simultaneously. The following chapter is focussed on kinematic measures of handwriting fluency and how they are affected by WM. In the chapter I will also investigate if there is a trade-off between recall performance and handwriting fluency.
Chapter 5 – The relationship between handwriting kinematics and working memory

Experiment 5.3 is adapted from the publication:

http://doi.org/1.1080/20445911.2015.1135930
In the previous chapters I have outlined that handwriting interferes with WM processes and that the interference is largely due to the motor component of the handwriting process. The results have supported previous research showing that handwriting does interfere with WM (Bourdin & Fayol, 1994) and this finding has been consistently replicated within the thesis. However, I have not yet attempted to replicate previous literature that has shown a relationship between WM and writing fluency (Benton, Kraft, Glover, & Plake, 1984; Brown, McDonald, Brown, & Carr, 1988; McCutchen, Covill, Hoyne, & Mildes, 1994; McCutchen, 2000; Olive & Kellogg, 2002; Peverly, Garner, & Vekaria, 2013).

Within the chapters in this thesis I have investigated the effect of handwriting on verbal serial recall when the two tasks are performed simultaneously. In the following experiments, I will aim to identify whether a relationship between measures of handwriting fluency (as measured by movement kinematics) are related to verbal WM performance when the two tasks are completed simultaneously. If a relationship is identified, this will indicate that a trade-off occurs, whereby when handwriting performance deteriorates verbal WM performance increases, or that when verbal WM deteriorates handwriting performance increases. If there is no relationship, this would suggest that handwriting captures attention automatically to maintain efficiency. The cost of this would result in a deterioration of verbal WM as attention is captured by handwriting, preventing resources from switching back to processing and maintenance.
5.1 Relationship between handwriting kinematics and verbal serial recall part 1

Previous studies have found correlations between writing performance and WM performance, indicating that as writing performance increases WM performance also increases. Specifically, McCutchen et al. (1994) found that fluent writers had higher scores on WM span tasks than dysfluent writers. McCutchen’s study used a very different methodology than what has been employed in the previous chapters. Firstly, the study investigated the effect within children over two different sessions. In the first session, the children were required to write essays, focusing on the spelling, grammar, and sentence structure. During the second session children completed two WM tasks (speaking span and reading span). The results were then compared between groups of skilled and relatively less skilled writers (based on performance on the essay tasks). The results showed that skilled writers performed better on the span tasks. These studies have investigated the relationship between writing and WM when the tasks have been performed separately. The analyses in these previous studies have only identified that there are differences between fluent writers and dysfluent writers on WM tasks. They have also only identified a relationship between writing (specifically essay performance, composition, and construction) and WM during tasks performed at separate times (McCutchen et al., 1994; McCutchen, 2000; Peverly, 2006; Peverly, Garner, & Vekaria, 2013).

McCutchen et al. (1994) investigated writing performance by indirectly measuring the production of written sentences after participants generated a sentence for each word presented during a reading span tasks. They found that writing performance and cognitive ability (on a lexical decision task) was higher for skilled writers on a reading span task. They also found that an increase in writing fluency might result in a decrease in WM load during writing. However, the actual kinematics of writing were not taken into account. Writing performance was based more on the students’ ability to generate quality written work
Handwriting Fluency

The measures do not account for the kinematics of writing and how they may be influencing the results. The suggestion that writing fluency interacts with WM load has some validity in relation to my current results. In this chapter I will investigate the relationship between handwriting kinematics as a measure of movement fluency and verbal serial recall performance.

More in line with the measures of fluency used within this chapter was a study by Connelly, Dockrell, and Barnett (2005). Their study investigated the handwriting efficiency of undergraduate students’ essay handwriting, under time-pressure. The measure of writing performance was a writing speed task based on Berninger, Mizokawa, and Bragg’s (1991) alphabet task, using children. The writing performance was measured by how many legible letters of the alphabet can be written in 1 minute. The test has been validated using a psychometric analysis of handwriting (see Berninger, 1999). Their results suggested that fluent writers utilise fewer resources allowing more to become available for other cognitive tasks (i.e., WM). This indicated that writing performance is only a good predictor of quality when cognitive load is high. This suggests that under difficult cognitive loading tasks, as demonstrated in the previous experiments, that writing quality/efficiency as measured by the kinematics might result in a decline in performance.

The processes involved in writing appear to overload WM’s ability to devote resources to both writing and information storage (Kellogg, 1996; McCutchen, 2000; Peverly, 2006). McCutchen (2000) suggests that due to the cognitive complexity of the writing process and the limited capacity of WM, trade-offs exist between task fluency (e.g., speed of writing) and information storage and retrieval. For example, when participants devoted attentional resources to the writing movement (as defined by the speed of letter production) their ability to store relevant information was adversely affected. However, when participants devoted attention to the storage of information, the fluency of their writing was hindered. This
switching and trading off resources is controlled by the central executive. Kellogg suggested that the central executive also plays a significant role in processing cognitive information during difficult tasks, such as writing.

Kellogg (1996) argues that the central executive may be impaired when higher-level cognitive demands are placed on it. For example, during complex tasks such as writing, it is unable to effectively devote attentional resources to both the storage of information and maintenance of fluent writing processes. The fluency of an individuals’ writing appears to play a role in determining their capacity to recall information (Peverly, 2006). Peverly found that the fluency of participants’ writing was correlated with how well they recalled information, with fluent writers able to recall more information from WM than dysfluent writers. However, in Peverly’s review, the data regarding fluency was typically gathered from one task and the data regarding recall was from a separate task. As such, it is unknown whether this pattern holds up when writing and WM tasks are completed simultaneously. To enable comparisons with previous studies that look at writing fluency and its effect on recall (e.g., Peverly, 2006), I will provide statistics for the mean kinematics of the writing movements (average stroke duration, average stroke size, and average absolute velocity). Further to this, I will investigate whether a relationship exists between the fluency of writing and number of words recalled from a concurrent WM task.

Peverly et al. (2013) investigated a similar mechanism. The main focus of the study was to investigate the relationship between handwriting speed, fine motor fluency, WM, attention, note-taking, and recall. The relationship they were most interested in was between note-taking and the other variables. However due to the nature of the thesis I will highlight what was found in the aforementioned study in regard to the relationships between verbal WM, handwriting speed, and fine motor fluency. Peverly’s results indicated that there was a significant relationship between Verbal WM (listening span; which is similar to the serial verbal recall task) performance and letter and composition speed on a 2-minute alphabet
fluency task. McCutchen’s (2000) review of the literature also identified a similar pattern of results between WM performance and the speed of handwriting letter production, in children and adults. McCutchen’s (2000) conclusions were supported by the findings of Berninger and Swanson (1994), who investigated children’s handwriting, and provided further evidence to suggest dysfluent writers engage more resources to process writing efficiently and have poorer WM performance. Further to this, McCutchen identified that when novice writers’ fluency improves that they are able to utilise long-term WM more efficiently.

Throughout the thesis, I have not yet investigated if a relationship between WM and handwriting fluency exists when the tasks are performed simultaneously. Due to some prominent limitations associated with a small sample size for conducting correlative analyses there has been insufficient data to confidently conduct an analysis for handwriting fluency and WM in the individual studies reported so far. To address this issue, an exploratory analysis using the combined data from the writing conditions from experiments 3.1, 4.1, and 4.2 will be conducted to see if a relationship between writing fluency and recall occurs with a larger sample size. In addition, I will also aim to identify if faster writers recall more words than relatively slower writers in line with previous research using speed as a measure of fluency (McCutchen, 2000; Peverly & Vekaria, 2013), however the measure of speed in this re-analysis of the data is based on the kinematics rather than letter or sentence composition.

For the purpose of this analysis, I will specifically look at the relationship between average absolute velocity, average stroke size, average stroke duration, average normalised jerk, and average number of strokes to Verbal WM (as measured by serial recall). If the combined data reveals a pattern of results that indicates a relationship between writing fluency and recall, then a follow up experiment will be conducted to replicate the findings.

It is worth noting that the research discussed above used a number of definitions and measures of fluency but much of this was directly or indirectly related to movement characteristics. Although I am primarily using handwriting kinematics related to speed and
size as the measure of fluency (based on Tucha et al. 2006) the more important question will be, is there any relationship between changes in a range of kinematics and changes in performance in a concurrent serial verbal recall task

**Methods**

**Participants**

A total of 50 participants’ data from experiments 3.2, 4.1 and 4.2 was combined; Only the data from the writing conditions was used.

**Design**

Kinematic measures were calculated for each movement stroke using the analysis options in MovAlyzeR. A stroke is the movement between points of zero velocity or local minima of absolute velocity. The writing kinematics are used as measures of writing fluency and calculated using the average stroke duration (ASD)—that is, the average duration of a single movement (stroke) in seconds; average stroke size (ASS)—that is, the average size of a single stroke (cm); and average absolute velocity (AAV)—that is, the speed of movement (cm/s), average normalised Jerk. For the writing kinematics, the overall mean measures were obtained for; stroke duration, stroke size, absolute velocity, normalised jerk and, number of strokes.

**Procedure**

Participant data for the writing condition was collated from 3 different experiments and input into an SPSS spread sheet. The data that was obtained was participants overall mean recall as well as mean recall for each serial position. I also obtained the mean kinematics occurring at times corresponding to each serial position. For example, the average absolute velocity was calculated for each 3 second time interval, with 0-3 seconds corresponding to serial position 1; 3-6 seconds corresponding to serial position 2 and so on (until 18 seconds).
The beginning of each 3 second time interval coincided with the initial presentation of each word. This was obtained for each kinematic variable. An example of the pattern of writing across the serial positions is presented in Figure 5.1.

**Results**

To investigate the pattern of writing for each individual across the experiments the average absolute velocity of each participant was plotted for each serial position. Visual inspection of Figure 5.1 shows that some participants were performing differently across serial positions with some participants writing performance relatively flat and unchanged across the serial position, while others have quite large peaks in absolute velocity, which resemble periods of dysfluency, however there appears to be no consistent pattern.

*Figure 5.1.* The pattern for AAV across the serial position for each participant.

**Correlations**

A bivariate Pearson correlation analysis was conducted to see if a relationship existed between recall and the measures of handwriting fluency. Table 5.1 displays the correlations
between the proportion of words recalled and each of the kinematic measures of fluency. None of the correlations reached significance.

Table 5.1.

*Bivariate Pearson correlations between the overall proportion of words recalled correctly with Average Absolute Velocity (AAV), Average Stroke Size (ASS), Average Stroke Duration (ASD), Average Normalised Jerk (ANJ) and the Average Number of Strokes (ANS).*

<table>
<thead>
<tr>
<th></th>
<th>AAV</th>
<th>ASS</th>
<th>ASD</th>
<th>ANJ</th>
<th>ANS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recall</td>
<td>r</td>
<td>-.011</td>
<td>-.072</td>
<td>-.087</td>
<td>-.083</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>.940</td>
<td>.620</td>
<td>.548</td>
<td>.565</td>
</tr>
</tbody>
</table>

To look at the relationship between recall and each kinematic measure of fluency in more detail I performed bivariate Pearson correlations between recall at each serial position with the average kinematic measurement at each serial position. Table 5.2 displays the results for this analysis. The results showed a positive relationship between recall and ANS at serial position 1, 2, and 3, but a negative relationship at serial position 5 and 6. This indicates that recall increased when participants completed more strokes during positions 1-3 but recall decreased when participants completed more strokes during positions 5 and 6. A positive correlation was also observed between recall, and AAV at serial position 3, showing that recall increased when the speed of the stroke was quicker.
Table 5.2

_Bivariate Pearson correlations between the mean proportions of words recalled at each serial position with the mean kinematic (ASD, ASS, AAV, ANJ and ANS) at each corresponding serial position._

<table>
<thead>
<tr>
<th>Serial Position</th>
<th>ASD</th>
<th>ASS</th>
<th>AAV</th>
<th>ANJ</th>
<th>ANS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.15</td>
<td>-.03</td>
<td>-.11</td>
<td>-.01</td>
<td>.36*</td>
</tr>
<tr>
<td>2</td>
<td>.23</td>
<td>-.02</td>
<td>-.13</td>
<td>.08</td>
<td>.38**</td>
</tr>
<tr>
<td>3</td>
<td>-.06</td>
<td>-.18</td>
<td>.28*</td>
<td>-.15</td>
<td>.40**</td>
</tr>
<tr>
<td>4</td>
<td>-.08</td>
<td>-.08</td>
<td>-.07</td>
<td>-.01</td>
<td>.22</td>
</tr>
<tr>
<td>5</td>
<td>-.14</td>
<td>&lt; -.01</td>
<td>-.04</td>
<td>.08</td>
<td>-.43**</td>
</tr>
<tr>
<td>6</td>
<td>-.13</td>
<td>.12</td>
<td>-.01</td>
<td>-.01</td>
<td>-.35*</td>
</tr>
</tbody>
</table>

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

To inspect if there was a pattern of handwriting fluency across the serial position, the mean measure of each kinematic at each serial position was plotted. On visual inspection of Figure 5.2, there appears to be changes in the size (ASS), duration (ASD), and smoothness (ANJ) of strokes during the different stages of the encoding across the serial positions, which corresponds with the pattern of recall. In the follow up experiment, it will investigate whether a similar pattern occurs, and utilize a mixed model approach to identify if there is an effect across the serial positions for handwriting fluency and verbal serial recall.
Figure 5.2. The pattern for recall and ANJ (a), ASS (b), ASD (c) and ANS across the serial position. The figure conceptualizes how the handwriting kinematics and recall may be interacting across the serial position.

Recall

To test if recall differed between the upper and lower quartiles of participants as determined by writing fluency, two groups were compared. Participants were split into upper and lower quartiles based on AAV. A factorial repeated measures analysis of variance was run to see if the two groups differed on verbal serial recall. The repeated measures ANOVA revealed no significant difference between the two groups. Figure 5.3 shows the pattern of recall for both the fast and slow writing groups.

To identify if the fast and slow writing groups differed significantly from one another at corresponding serial positions, a series of linear contrasts were conducted. For example, recall at serial position 1 was compared between the fluent and relatively dysfluent group. The
linear contrasts revealed a significant difference between the groups at serial position 4, $F(1, 14) = 6.94, p = .02$. [Bonferroni 95% CI: -.41 - -.04] and; Serial position 5 $F(1, 14) = 16.64, p = .001$ [Bonferroni 95% CI: -.47 - -.15], with significantly more words recalled in the faster writing group.

Figure 5.3. Mean word recall at each serial position as a proportion of correct responses for participants with fast and slow handwriting speed. Vertical lines represent the standard error above and below the mean for each serial position.
Discussion

The analyses of all the handwriting conditions was conducted to identify if a relationship between writing fluency and verbal recall existed. Based on the results plotted in Figure 5.2 there is a pattern of handwriting across the serial position that resembles the pattern of recall for the size (ASS), duration (ASD), smoothness of movement (ANJ) and efficiency of strokes (ANS). This pattern will be investigated in the following experiment. However, I could not replicate previous literature utilizing speed of writing as the main measure of fluency nor was I able to identify a relationship between participants mean overall recall performance and mean fluency scores, except for the number of strokes (ANS) which only showed significant relationships at individual serial positions and not for the overall mean score.

The analysis of this data is only exploratory and there are a few potential confounds/issues related to this analysis of the data, however, it still provides some insight to how writing across a serial position interact to predict verbal serial recall. The main concern with the reliability of this analysis is the sample, it is possible that some of the data across experiments is from participants who have completed more than one of these experiments. Due to ethics restrictions, it is not possible to remove these participants from the analysis. This may skew the results as the same participant is sampled more than once, and the portion of fluent and dysfluent writers may not be an accurate representation of the population. Furthermore, as each of these were conducted with different other conditions and on different equipment, the data might not be directly comparable. Nonetheless, the analysis has provided some insight into how writing fluency might be interacting with serial position and its relationship to verbal serial recall. While the analysis may have some confounds, it provides a basis for future exploration of this phenomenon. The next experiment will attempt to identify
if the pattern of recall across the serial position curve can be predicted by the pattern of handwriting across the serial position with a new sample of participants.

5.2 Relationship between handwriting kinematic and verbal serial recall part 2

Experiment 5.2 was conducted to replicate the findings found in re-analysis of data in 5.1. The analysis I conducted in the first experiment used data from multiple experiments reported in the previous chapters and collapsed them together. In doing this, I could not control for differences in experimental procedures and the different devices used as well as identifying if some of the participant data was from individuals who participated in more than one experiment. To address this issue, I conducted a further experiment to see if I could successfully replicate the findings from the reanalysed experimental data in 5.1.

Method

Participants

Participants were recruited from the general public and the university. A total of 27 participants completed the experiment, with only 25 participants (Males $n = 10$; Female $n = 15$) completing the experiment correctly, two participants did not follow instructions correctly and were removed from the analysis.

Apparatus

The experiment was conducted in a lab set-up with a Microsoft surface pro and stylus to display the stimuli and record the movements of participants. MovAlyzeR displayed the movements on tablet screen in real time and recorded the pen movements. The participants were given a pair of headphones to listen to a pre-recorded list of words spoken by the researcher, also presented via MovAlyzeR. The stimuli used in this experiment were identical
to the word lists used in previous experiments, however, a new order of word lists was generated.

Procedure

The procedure for this experiment was identical to the handwriting condition in experiment 4.1. Participants were instructed to move the stylus through the ‘START’ icon to start the list of six words. They were then instructed to begin writing down the words they were listening to during the presentation of the first word. Participants were told to write in their natural handwriting and attempt to write down each word even if they were unsure of the correct spelling. It was emphasised that they must attempt to write down each word. Participants continued writing until they heard a beep at the end of the list; this was to prompt them to stop writing. At this point, the participants’ writing disappeared from the screen and ‘RECALL’ appeared on the centre of the screen. Participants then practiced the handwriting task until they were comfortable and the experimenter was comfortable with their ability to use the program. At this point, the experimenter started the handwriting condition and left the room, participants were asked to notify the experimenter once the condition had been completed.

Results

To investigate the pattern of writing for each individual across the experiments the velocity (AAV) of each participant was plotted for each serial position. Visual inspection of Figure 5.4 shows that some participants were performing differently with some participants writing performance relatively flat and unchanged across the serial position, while others have quite large peaks in writing fluency which resemble periods of dysfluency. Overall correlations between writing fluency and recall are investigated using Bivariate Pearson
Correlations. The changes in performance across the serial positions are analysed using a linear mixed model.

Figure 5.4. The pattern for AAV across the serial position for each participant.

Correlations

A bivariate Pearson correlation analysis was conducted to see if a relationship existed between recall and the measures of fluency. Table 5.3 displays the correlations between the proportion of words recalled and each of the kinematic measures of fluency. A significant positive correlation occurred between recall and ANJ, indicating that as participants control and smoothness of their movement became dysfluent, their recall increased, indicating that a trade-off may have occurred.
Table 5.3.

Bivariate Pearson correlations between the overall proportion of words recalled correctly with the overall Average Absolute Velocity (AAV), Average Stroke Size (ASS), Average Stroke Duration (ASD), Average Normalised Jerk (ANJ) and the Average Number of Strokes (ANS)

<table>
<thead>
<tr>
<th></th>
<th>ASD</th>
<th>ASS</th>
<th>AAV</th>
<th>ANJ</th>
<th>ANS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recall</td>
<td>.312</td>
<td>.257</td>
<td>.275</td>
<td>.479*</td>
<td>-.351</td>
</tr>
<tr>
<td>p</td>
<td>.129</td>
<td>.215</td>
<td>.183</td>
<td>.015</td>
<td>.085</td>
</tr>
</tbody>
</table>

* Correlation is significant at the .05 level (2-tailed).

To look at the relationship between recall and each kinematic measure of fluency in more detail I performed bivariate Pearson correlations between recall at each serial position with the average kinematic measurement at each serial position, Table 5.4 displays the results for this analysis. The analysis showed that moderate positive correlations occurred at serial position 3, between recall, AAV and ANJ showing that as speed increased and control of movement became dysfluent that recall increased. At serial position 4 moderate positive correlations occurred between recall and ASD, ASS, ANJ. This suggests that recall increased when participants’ strokes took longer, became larger, faster, and less controlled. There was also a moderate negative correlation between ANS and recall indicating that recall increased when participants completed fewer strokes. This suggests that a trade-off in writing fluency occurs to increase recall performance at serial positions 3 and 4.
Table 5.4.

_Bivariate Pearson correlations between the mean proportion of words recalled at each serial position with the mean kinematic (ASD, ASS, AAV, ANJ and ANS) at each corresponding serial position._

<table>
<thead>
<tr>
<th>Serial Position</th>
<th>ASD</th>
<th>ASS</th>
<th>AAV</th>
<th>ANJ</th>
<th>ANS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-.03</td>
<td>.046</td>
<td>.13</td>
<td>.127</td>
<td>-.094</td>
</tr>
<tr>
<td>2</td>
<td>.006</td>
<td>-.01</td>
<td>.143</td>
<td>.294</td>
<td>-.066</td>
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<tr>
<td>3</td>
<td>.243</td>
<td>.35</td>
<td>.507</td>
<td>.441</td>
<td>-.369</td>
</tr>
<tr>
<td>4</td>
<td>.528**</td>
<td>.415*</td>
<td>.346</td>
<td>.435*</td>
<td>-.435*</td>
</tr>
<tr>
<td>5</td>
<td>.363</td>
<td>.182</td>
<td>.054</td>
<td>.38</td>
<td>-.332</td>
</tr>
<tr>
<td>6</td>
<td>.325</td>
<td>.102</td>
<td>-.061</td>
<td>.256</td>
<td>-.209</td>
</tr>
</tbody>
</table>

_Mixed linear model_

To take the analysis one step further a mixed linear model was applied. This was to see if the pattern of recall across the serial positions could be predicted by changes in writing fluency across the serial positions. Due to high correlations between recall at each serial position, (see table 5.6) an autoregressive, maximum likelihood mixed linear model was employed. Recall was set as the dependent variable with participants as a random effect and the fixed effect were set as serial position and the kinematic variable (AAV, ASS, ASD, ANJ and ANS). No significant model was found for any of the kinematic variables, indicating that the pattern of recall across the serial position could not be predicted by changes in handwriting fluency.
Table 5.6

**Bivariate Pearson correlations for the proportion of words recalled at each serial position**

<table>
<thead>
<tr>
<th></th>
<th>SP1</th>
<th>SP2</th>
<th>SP3</th>
<th>SP4</th>
<th>SP5</th>
<th>SP6</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1</td>
<td>r</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP2</td>
<td>r</td>
<td>.516**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP3</td>
<td>r</td>
<td>.553**</td>
<td>.779**</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP4</td>
<td>r</td>
<td>.014</td>
<td>.309</td>
<td>.453*</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>SP5</td>
<td>r</td>
<td>.161</td>
<td>.263</td>
<td>.251</td>
<td>.637**</td>
<td>1</td>
</tr>
<tr>
<td>SP6</td>
<td>r</td>
<td>.403*</td>
<td>.522**</td>
<td>.386</td>
<td>.425*</td>
<td>.684**</td>
</tr>
</tbody>
</table>

**Recall**

To test if recall differed between the upper and lower quartiles of participants as determined by writing fluency two groups were compared. Participants were split into upper and lower quartiles based on AAV. A repeated measures analysis of variance was run to see if the two groups differed on verbal serial recall. The repeated measures ANOVA revealed no significant difference between the two groups.

To identify if the fast and slow writing groups differed significantly from one another at corresponding serial positions, a series of linear contrasts were conducted. For example, recall at serial position 1 was compared between the slow and relatively fast writing groups, then at serial position 2, and so on. The linear contrasts revealed a significant difference between the groups at serial position 3, $F(1, 10) = 8.910, p = .014$. [Bonferroni 95% CI: -.58 - -.08]. Figure 5.5 shows the pattern of recall for both the fast and slow writing groups, showing that fast writers recalled significantly more words than relatively slower writers at serial position 3.
Figure 5.5. Mean word recall at each serial position as a proportion of correct responses for participants with fast and slow handwriting speed. Vertical lines represent the standard error above and below the mean for each serial position.

Discussion

Previous research has shown that writing fluency is correlated with performance on WM tasks, such as the reading span and speaking span (McCutchen et al., 1994). A majority of these studies have only shown this relationship between two tasks performed independently of one another. The current analysis aimed to identify if this relationship would occur when performing a writing task and WM task simultaneously. To some extent the findings have supported this but the results are not robust enough or consistent across serial position to draw any definitive conclusions and so requires further exploration. However, this is beyond the
scope of my thesis. In support of the relationship between WM and writing fluency in experiment 5.2 I identified a positive relationship between the mean overall control and smoothness of movement (ANJ) and the overall mean proportion of words recalled correctly. What this indicates is that recall increases as participants’ movements become less controlled or jerky (ANJ). This may indicate a trade-off between recalling more words at the cost of maintaining fluent movements. This provides some insight into performance across the serial positions.

When looking at this effect at each serial position we see that at serial position 3 and 4 a positive relationship occurs between recall and AAV and ANJ at serial position 3 while at serial position 4 recall is correlated positively with ASD, ASS and ANJ but negatively with ANS. This is further evidence that a trade-off could be occurring between writing fluency and recall, however the relationship is only observable at serial positions 3 and 4 when cognitive resources are thought to be at their minimum. Therefore, in order to increase recall during the middle serial positions the fluency of handwriting is decreased in order to maintain efficiency on recall. Specifically, the control of the movement decreases, which results in an increase in stroke size, duration, and participants completing fewer strokes which is reflective of the writing being less legible or the writing movements not being efficient.

From the findings in the reanalysis of the data in 5.1 and experiment 5.2, I can conclude that when performing a handwriting task while simultaneously completing a verbal WM task that there is no consistent relationship between handwriting kinematics and verbal working memory. This suggests that the relationship observed by McCutchen et al. (1994, 1996) and Peverly (2006), between a WM and writing task when performed independently of one another does not occur when the two tasks are performed simultaneously. This may indicate that to some extent there is little variability in the handwriting kinematics in this study due to the consistency of the participants’ movements or due to the nature of the task itself (e.g. the small number of words written per list compared to paragraphs of writing).
However, if there really is no relationship between changes in handwriting kinematics and changes in recall, then it would suggest that handwriting is capturing WM resources continuously in order to maintain a minimal level of efficiency at the cost of WM performance. To investigate this the following experiment was designed to specifically test if gross changes in handwriting fluency occur when participants simultaneously perform a handwriting task while recalling the word lists, compared to performing a handwriting task without the need to recall word lists.

5.3 Handwriting without Recall

Handwriting is a demanding task and when attention is divided between multiple processes, efficiency tends to suffer (Berninger, 1999; Graham, Harris, & Fink, 2000; McCutchen, 1995). This experiment is designed to test if there is a change in writing fluency when writing with a concurrent serial recall task compared to writing without a concurrent serial recall task. That is, does the addition of a serial recall task change the writing kinematics? This is in direct contrast to the listening and listening with handwriting conditions. I aim to investigate whether an increase in writing fluency occurs in the absence of a WM task.

I have outlined previously that I suspect the decrease in WM performance while writing is due to cognitive resources being diverted away from WM processes. I assume that this is due to the complexity of the movements. However, with limited resources available it is plausible that if resources must be shared between both WM and writing, then the performance of both tasks would be performed worse than if the tasks were performed independent of one another. This experiment investigates handwriting fluency at the encoding phase of a verbal serial recall task and handwriting fluency while writing down words without needing to encode and recall items. Due to both the handwriting and WM tasks utilising a
common pool of resources (Berninger et al., 1992; Bourdin & Fayol, 1994, 2002; Brown et al., 1988; Graham et al., 1997; Kellogg, 1996) it could be expected that if resources are diverted to encoding/maintenance and split between both, then handwriting will be affected. It is important to note that some of these studies measured attention in children (e.g., Berninger et al., 1992; Bourdin & Fayol, 1994), therefore it is likely there are differences in the attentional mechanisms, nonetheless, attention seems to be integral for adult writing as well (Peverley, 2006). However, if resources are not diverted to encoding/maintenance than writing will not be affected. I will further investigate if a relationship exists between a concurrent handwriting task and the proportion of words recalled across all experiments and test this assumption in a newly designed experiment.

**Method**

*Participants*

The experiment included fifteen voluntary (Females, $n = 10$; Males, $n = 5$) participants from the university and general public. The mean age of participants was 32.45 years ($SD = 1.23$)

*Apparatus*

The experiment was conducted in a lab set-up with a Microsoft surface pro and stylus to display the stimuli and record the movements of participants. MovAlyzeR displayed the movements on tablet screen in real time and recorded the pen movements. The participants were given a pair of headphones to listen to a pre-recorded list of words spoken by the researcher, also presented via MovAlyzeR.
Procedure

The writing with recall condition was identical to the writing condition used in experiment 4.2. Participants listened to word lists while writing the words down using the Microsoft surface pro tablet and stylus via MovAlyzeR. It was emphasised that they would need to recall the words they were listening to. The writing without recall condition was identical to this, however it was emphasised that there was no recall phase and they did not need to attempt to remember the word lists. Instead the ‘RECALL’ that appeared on the screen was replaced with ‘CONTINUE’ and participants waited until the ‘START’ button appeared to start the next list. This ensured the timing between starting each list was controlled. The two conditions were counterbalanced.

Results

Results were compared for the handwriting with recall condition and the handwriting without recall condition through repeated measures Analysis of Variance (ANOVA) for each individual kinematic measurement of handwriting fluency.

Recall was measured as the proportion of correct responses at each serial position. Figure 5.6 summarises the mean words recalled in the handwriting with recall condition. The repeated measures ANOVA revealed a significant main effect for serial position, $F(5, 70) = 54.39, p < .001, \eta_p^2 = .8$. Indicating there were differences across the serial positions for recall consistent with the pattern of results from experiment 4.1 and 4.2.
Handwriting fluency

To test if there were differences in handwriting fluency during the handwriting with recall and handwriting without recall conditions a series of repeated measures ANOVAs were conducted for each kinematic variable across the serial positions. Table 5.7 presents the statistics for each kinematic variable for the repeated measures ANOVA, analysing the difference in pattern of handwriting kinematics in the recall and no recall handwriting conditions. The results revealed no significant mean difference between measures of handwriting fluency or an interaction between the two conditions indicating that the addition of processing items in WM did not reduce the performance of handwriting movements. However, there was a significant effect of serial position for average stroke size, suggesting that there were some differences in the size of the movements across the serial positions. There was also a non-significant tendency towards an effect of serial position for duration.

Figure 5.6. Mean proportion of words recalled at each serial position in the writing with recall condition.
velocity, and jerk, with higher values at or near serial position 4, corresponding with the low points on the serial recall curve.

Table 5.7

_The results for the repeated measures analysis of variance for ASD, ASS, AAV, and ANJ for Condition, Serial Position, and Condition x SP interaction. The degrees of freedom (df), F statistic, probability, and measure of effect size (ηp²) are presented._

<table>
<thead>
<tr>
<th>Kinematic</th>
<th>Variable</th>
<th>df</th>
<th>F</th>
<th>p</th>
<th>ηp²</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASD</td>
<td>Condition</td>
<td>1, 14</td>
<td>.42</td>
<td>.528</td>
<td>.03</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>4.13, 27.73</td>
<td>2.11</td>
<td>.089</td>
<td>.13</td>
</tr>
<tr>
<td></td>
<td>ASD*SP</td>
<td>2.70, 37.78</td>
<td>.86</td>
<td>.458</td>
<td>.06</td>
</tr>
<tr>
<td>ASS</td>
<td>Condition</td>
<td>1, 14</td>
<td>.14</td>
<td>.716</td>
<td>.01</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>2.57, 35.95</td>
<td>3.31</td>
<td>.037*</td>
<td>.19</td>
</tr>
<tr>
<td></td>
<td>ASS*SP</td>
<td>2.62, 22.29</td>
<td>1.93</td>
<td>.149</td>
<td>.12</td>
</tr>
<tr>
<td>AAV</td>
<td>Condition</td>
<td>1, 14</td>
<td>.01</td>
<td>.915</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>2.89, 40.73</td>
<td>2.85</td>
<td>.051</td>
<td>.17</td>
</tr>
<tr>
<td></td>
<td>AAV*SP</td>
<td>2.27, 23.19</td>
<td>1.05</td>
<td>.37</td>
<td>.07</td>
</tr>
<tr>
<td>ANJ</td>
<td>Condition</td>
<td>1, 14</td>
<td>.85</td>
<td>.372</td>
<td>.06</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>3.13, 43.76</td>
<td>2.54</td>
<td>.066</td>
<td>.15</td>
</tr>
<tr>
<td></td>
<td>ANJ*SP</td>
<td>3.09, 43.24</td>
<td>1.42</td>
<td>.25</td>
<td>.09</td>
</tr>
</tbody>
</table>

*Note: ASD - average stroke duration; ASS - average stroke size; AAV - average absolute velocity; ANJ - average normalised jerk

In addition, Figure 5.7 shows the pattern of handwriting across the serial position for each kinematic variable in the handwriting with recall and handwriting without recall conditions. The figures further emphasise that the pattern of handwriting at each serial position in the recall and no recall conditions were nearly identical.
**Discussion**

This experiment was designed to specifically test if the demands of a verbal WM serial recall task resulted in a diversion of cognitive resources that would be reflected in a decline in handwriting movement performance. However, no such effect was found. The results support the argument that sizeable resources are not diverted from handwriting to encoding/maintenance and thus the allocation of resources to handwriting remains relatively constant in the presence or absence of a WM task. That is, even when they were explicitly instructed that they would not need to recall the words and that they should not rehearse them.

The lack of differences in the kinematics of handwriting movements between the two conditions tells us something interesting about how handwriting may be interfering with WM processes. In the previous chapters, I consistently demonstrated that handwriting significantly impairs WM compared to listening, with an increase in WM performance in the absence of
Handwriting Fluency

handwriting. I argued that the complexity of the handwriting movements and the need to encode/maintain items for later recall would result in both tasks capturing substantial resources for optimal performance. If resources are more evenly shared between handwriting and memory processes, there should have been an incremental decrease in the performance of both tasks when performed concurrently. However, since there was no change in kinematics, it appears that resources were predominantly captured and held by the handwriting task.

This result is of particular importance and indicates that in order to perform the task at all (and maintain efficiency) the handwriting process is not inhibited during this WM task. Therefore, the interference that has been found in the experiments 4.1 and 4.2 is not an incremental decrease in the performance of both handwriting fluency and recall. Instead, it is a trade-off that maintains a constant level of handwriting fluency at the cost of efficiently processing and maintaining information within WM. This also explains why there was no significant relationship found between handwriting kinematics and verbal recall. The handwriting task is maintained at a relatively constant level, this process appears to be automatic and unable to be inhibited. This results in meaningless differences in handwriting performance which is noticeable in the lack of variation in the kinematic measure in experiment 5.2. The cost associated with maintaining handwriting efficiency might result in attention being captured for significant periods, limiting the switching of attention back to the processing and maintenance of items in WM.

These findings provide insight into how handwriting may be interacting with WM. It demonstrated that handwriting performance does not deteriorate when performing a concurrent WM task despite the strong deterioration in recall found in the handwriting and pseudo-handwriting condition in experiment 4.1 and 4.2. This finding is in contrast to studies identifying that handwriting fluency tends to suffer when attention is divided (Berninger, 1999; Graham et al., 2000; McCutchen, 1995; Racine, Majnemer, Shevell, & Snider, 2008). It is important to note that some of these studies measured attention in children, therefore it is
likely differences in the attentional mechanisms. Nonetheless, attention seems to be integral for adult writing as well (Peverley, 2006). The results suggest that there needs to be a level of consistency of movement in order to complete the handwriting task. The way participants write does not substantially change when this secondary task is performed simultaneously. This indicates that participants do not substantially divert attention away from the handwriting task or reduce the quality of their handwriting to compensate for the demands of the secondary task but maintain performance at a relatively constant level. This could be explained by handwriting and drawing being overlearned skills (Longstaff & Heath, 1997), which are to some extent automatic and require a basic level of performance for the tasks to be achieved at all. As such, the movements required to handwrite or draw automatically capture resources. As a consequence, performance on these tasks cannot be inhibited to any great degree.

The findings thus far, have identified that verbal serial recall deteriorates when concurrently completing a handwriting task. I suspected that this is due to handwriting capturing attention for significant periods, reducing the ability for resources from switching back to processing and maintenance of to-be-remembered words. The experiments conducted in the Chapter 5, have supported this notion. I did not identify a relationship between handwriting kinematics and verbal serial recall, as there is little variability in handwriting fluency across the serial positions. In experiment 5.3, I found that there is no difference in handwriting fluency measures when concurrently performing and verbal serial recall task compared to handwriting without the need to recall. This indicates that handwriting fluency captures attention in order to maintain a minimum level of efficiency; this capturing is automatic and cannot be inhibited. I can conclude that in terms of performing handwriting and WM tasks simultaneously, that verbal serial recall suffers while handwriting fluency is unaffected. Essentially, in order to perform a handwriting task at all, attention is captured to
maintain and perform the complex motor movements. This in turn could be preventing the efficient switching of attention back to processing and maintenance.

While the results so far are clear and consistent, it may be that the results could change if the load is increased further, to an extent that both writing and verbal WM performance is affected. This would also test the argument that one of the main mediating factors for performance is the attentional demands placed on the cognitive/motor system. In the following chapter I will investigate whether increasing the complexity of a concurrent attention-demanding task will reduce performance for verbal serial recall and handwriting. This will confirm and identify if handwriting and WM share a common attentional resource, and when attention is captured by an increasingly demanding task that performance on a working memory tasks decreases.
Chapter 6 – An investigation of shared attention
In the previous chapters I have demonstrated that handwriting and pseudo-handwriting decrease verbal serial recall to a similar extent. I argue that this is largely due to the motor component of handwriting, as there is little additional deterioration in WM performance due to the verbal component of handwriting. Furthermore, the results from chapter 5 suggests that handwriting performance does not change during a WM task, indicating that handwriting automatically captures resources in order to perform the task with some level of efficiency. Taken together, this suggests that resources are captured and held for long periods of time by the handwriting movements. To further test whether handwriting movements capture attention while performing a concurrent WM task, the following experiment employs a triple task paradigm. The additional task is an attention demanding tapping task, which allows a simple manipulation of the tasks difficulty to increase the attentional demands.

The emergent property model of WM (Postle, 2006) explains the neurological feasibility of WM as a cognitive construct. It seems neurologically improbable that a separate attentional resource would exist for WM and an alternative resource for other cognitive tasks. It is more likely that an emergent property provides a more realistic explanation of the neurological system (Postle, 2006). Here, attention is defined as an internal mechanism that is governed by the dorsolateral prefrontal cortex (DLPFC) to perform multiple cognitive tasks (Brown, Collier, & Night, 2013; Clarke, Browning, Hammond, Notebaert, & MacLeod, 2014; Postle, 2006; Schneider, Schote, Meyer, & Frings, 2014). When performing a cognitive task, the DLPFC focuses attention on the neurological region needed to process, maintain, and execute that task. For example, when performing a verbal WM task, the DLPFC has been implicated in focussing attention on the left posterior perisylvian areas, which are responsible for processing and understanding speech (Postle, 2006). Consistent with the TBRS model, attention is a limited resource that is utilised by multiple cognitive tasks. When the focus of attention shifts or splits between multiple tasks, resources become scarce. Alternatively, the
DLPFC is unable to maintain the focus of attention on all neurologically activated regions, meaning that when performing multiple tasks simultaneously, performance tends to suffer.

Ransdell, Levy, and Kellogg (2002) investigated how resources are allocated during a WM and writing task. Fluent and relatively dysfluent writers completed a serial recall task of six digits while concurrently writing essays. The participants were required to continuously maintain a set of 6 digits while writing essays. As a measure of cognitive performance, participants' writing performance and quality was analysed. This was done by measuring the number of words written per minute, writing quality (e.g., sentence length, length, and frequency of pauses). Their results identified that writing performance deteriorated when trying to maintain 6 digits. They argue that resources that are normally unaffected by dual tasks were utilised by the writing processes in order to maintain fluency. A significant difference between the two groups under low and high WM loading tasks was also observed. One of their conclusions suggested that when the complexity or difficulty of a secondary task is increased, the resources available to perform the two tasks might become overloaded. This results in a decrease in writing performance (as defined in their study) to allow greater efficiency on the WM task. This finding is in contrast to those presented in previous chapters. It is possible that the differences in methodology employed in Ransdell et al.’s study compared to the methodology I employed in the experiments is why I have not previously extended these findings. However, this also points to limitations for the robustness of a relationship between handwriting fluency and working memory. The research has observed detrimental effects on WM and writing tasks when a cognitively demanding secondary task is performed. It is unclear whether the central pool of resources is only utilised by tasks that rely on WM (e.g. serial recall and handwriting) or if demanding tasks that do not rely on WM processes also decrease performance.

The role of attention in cognition has been demonstrated previously by utilising finger-tapping tasks (Chavez, Trautt, Brandon, & Steyaert, 1983; Friedman, Polson, & Dafoe,
Kemper et al. (2003) compared WM performance (as measured by speech fluency) between younger and older adults. Participants completed nine separate tasks, including talking alone, and completing a complex or single finger tapping task alone or while talking (Kemper et al., 2003). Their finger tapping paradigm required participants to complete a tapping sequence using four fingers as quickly and accurately as possible (for 5 minutes). The simple tapping task required participants to tap as quickly as possible (for 5 minutes) with their index finger.

Kemper et al. (2003) found that performance only deteriorated significantly when the finger tapping complexity was increased. That is, when speaking while completing a complex tapping sequence participants needed to intermittently cease or break the pattern of tapping to carry on a conversation. However, they were able to maintain a conversation efficiently while performing a rapid single finger tap. Other studies have also found that finger tapping tasks can disrupt motor planning (i.e. prospective motor coding) and spatial/locational WM (e.g. Salway & Logie, 1995; Smyth & Pendleton, 1990). Notably, these studies utilised quite complex finger tapping sequences. For example, Smyth and Pendleton (1990) required participants to tap with their non-dominant hand in a clock-wise motion on four different keys. This task requires multiple coordination requirement between fingers and a spatial requirement to maintain position and motion in a clockwise manner. These tapping sequences require a WM component to maintain the ordinal sequence of multiple taps. These findings further emphasise that as the demand of a secondary task is increased the resources needed to perform the two tasks becomes limited and reduces performance. However, it has not been investigated whether increasing the attentional demand of a concurrent tapping task that does not rely on WM will reduce verbal WM and writing fluency performance.

The current experiment explores this concept by investigating if an attention demanding secondary task that does not rely on WM would contribute to a reduction in verbal serial recall and handwriting fluency. For example, when performing a verbal WM task, the
DLPFC would focus attention on the left posterior perisylvian areas (Postle, 2006). If also completing a concurrent handwriting task, the DLPFC will need to focus attention on the motor component of handwriting (e.g., primary motor, sensorimotor cortex, and supplementary motor areas) and the verbal component of handwriting (e.g., ventral premotor cortex, posterior/inferior temporal cortex; Planton, Jucla, Roux, & Démonet, 2013). When completing an additional concurrent finger tapping task that does not rely on WM, the DLPFC will also need to focus attention on the right motor cortex and left cerebellum to maintain a finger-tapping task with the non-dominant hand (Nyberg, Eriksson, Larsson, & Marklund, 2006). If a non-WM related task (such finger tapping) reduces performance on both handwriting and WM tasks, this would provide evidence that the same attentional resource is utilised by multiple cognitive tasks and that this becomes particularly noticeable when the multiple task requirements overload resources. This will strengthen the cognitive and neurological models of attention, WM, and handwriting and suggest that the DLPFC becomes limited when it must focus attention between multiple neurological regions.

To investigate this, I conducted an experiment that would incrementally increase the attentional load of a concurrent tapping task while completing a serial verbal recall and handwriting task. Participants completed three WM tasks. They were required to recall word lists after listening to words while producing handwriting like movements (tracing inverted el loops) with (1) no tapping (pseudo-handwriting condition), (2) simultaneously producing finger taps with a single finger with their non-dominant hand (single tap condition), and (3) simultaneously alternating finger taps between two fingers with their non-dominant hand (double tap condition). The single and double finger tapping tasks were chosen as they allow a small increase in attentional demand without relying on WM performance to maintain complex tapping sequences. It is important to note that in this experiment, increases in task complexity are due to the introduction of the finger tapping tasks. For example, the tasks
Attention

without tapping is the least complex task; the single finger tapping task is of moderate complexity; and the most complex is the double tapping task.

Consistent with findings from previous verbal serial recall studies (e.g., Allen & Hulme, 2006; Logie, Della Sala, Wynn, & Baddeley, 2000; Pattamadilok et al., 2010), it is expected that a primacy and recency effect will be observed for all the conditions I hypothesise that recall will differ significantly between all three conditions and further investigate if differences occur at individual serial positions. Just as Tindle and Longstaff (2015, 2016) found, I expect that difference will occur between conditions at serial positions 1-4. Specifically, recall performance will be best in the pseudo-handwriting condition, moderate in the single finger tapping condition, and poorest in the double tapping condition. Although Kemper et al. (2003) only found a difference for a complex-tapping task, I expect that the additional load of tracing loops while tapping with a single finger will be sufficient to limit the time attention is switched back to processing and maintenance (Barrouillet & Camos, 2007). Furthermore, as I am employing a serial recall task it is expected that order errors may occur (Acheson & MacDonald, 2009; Henson, 1998), i.e. when an item is recalled correctly but in the incorrect serial position (Gathercole, 2008). Order errors will therefore be reported as they provide insight into how each task is affecting the underlying processes of WM (Acheson & MacDonald, 2009). For example, if the tapping task prevents accurate phonological encoding a higher proportion of order errors should be observed (Acheson & MacDonald, 2009).

I expect that decrements in performance will also be noticeable in the kinematics of the pseudo-handwriting movements. As found in Ransdell, Levy, and Kellogg (2002), I expect that as the task complexity increases that handwriting fluency (as measured by kinematics of strokes) will decrease between all three conditions. With fluency being the best in the pseudo-handwriting condition, moderate in the single finger tapping condition, and poorest in the double tapping condition. To gain greater insight into how performance
changes during the tapping tasks, the accuracy, timing, and frequency of taps produced will be analysed for the single and double tapping conditions. The timing of the taps will also be compared to the target speed (500 ms) for both conditions.

**Methods**

**Participants**

Fifteen participants completed the experiment, including eight males and seven females. Participants were recruited voluntarily with no incentives offered for participation. The mean age was 35.15 ($SD = 12.25$). All participants provided informed consent before completing the study. The Southern Cross University Human Research Ethics Committee approved this study.

**Design**

The experimental conditions included a *pseudo-handwriting*: listening while drawing combinations of small and large loops; *single tap*: listening while drawing combinations of small and large loops and tapping with a single finer; and *double tap*: listening while drawing combinations of small and large loops and alternating tapping between two fingers. The dependent variables were the proportion of words recalled in the correct serial position, measures of writing fluency and tapping speed (ms).

An analysis of writing kinematics was used to assess changes in writing fluency for all the conditions as measured by the average stroke duration i.e. the average duration of a single movement (stroke) in seconds. Average size i.e. the average size of a single stroke (cm). Average absolute velocity i.e. the speed of movement (cm/second). Lastly, average normalised jerk, which is a unitless measurement that is related to how smooth and controlled a movement is. For example, high average normalised jerk is reflective of dysfluent movements (Caligiuri, Teulings, Dean, Niculescu, & Lohr, 2011). When I refer to writing fluency, I looked for relatively lower average stroke duration (fast strokes; seconds), accurate
average stroke sizes (cm), high average absolute velocity (cm/sec), and low average normalised jerk.

The dependent variables for measuring tapping performance was the tapping speed and the deviation in tapping speed. Tapping speed, was measured as the time between consecutive taps. The deviation in tapping speed was the difference in reaction in time between two consecutive taps. Both these measures were calculated as the mean performance at each serial position. This was calculated by calculating the tapping speed and deviation in tapping speed at each 3 second interval, from the start of the presentation of the first word to the end of the presentation of the last word (i.e., 18 seconds).

Apparatus

The shapes used in the experiment were inverted small and large loops that were designed using combinations of the letters ‘e’ and ‘l’, the same as experiment 4.2.

The finger tapping task was set up on a second computer and responses were recorded using e-prime, participants were unaware of the second computer and did not need to interact with the interface and was controlled from outside the testing laboratory by the experimenter. To start the finger-tapping portion of the experiment, MovAlyzeR was set up to play a set of beeps for 5 seconds before the word lists began. The beeps were sine waves set to 440 Hz for duration 5 ms with an inter-stimulus interval of 500 ms. There were two tapping conditions, the first was a single finger tap, this required participants to tap the ‘>’ button on the keyboard with their index finger on their non-dominant hand in time with the beeps (500 ms). The second condition was a double tapping condition, this required participants to alternate finger taps between ‘<’ button and ‘>’ buttons on the keyboard using their index and middle finger on their non-dominant hand.

Procedure
The procedure for the pseudo-handwriting condition was the same as the procedure for the tracing of loops for the pseudo-handwriting condition in experiment 4.2. Participants listened to lists of 6 words while simultaneously tracing over combinations of inverted e’s and l’s. After the 6 words had been presented participants recall the words aloud in the order they were presented.

When completing the single finger tapping task participants heard a series of beeps for 5 seconds (after placing a stroke through the ‘START’ button). Participants were instructed to begin tapping as soon as they heard the beeps using the ‘>’ button on the keyboard in time with the beeps, with their index finger, on their non-dominant hand. After the first three seconds of the beep sequence, the inverted loops appeared on the screen for participants to begin tracing, while simultaneously maintaining the tapping speed. Once the beeps had ceased, the presentation of the word list began and participants were required to maintain the tapping speed and trace the inverted loops while concurrently listening to the presentation of the word lists. Participants were told to maintain the speed of the tapping as accurately as possible while continuously tracing the loops until they heard a beep at the end of the list; this was to prompt them to stop and begin recall.

The double finger-tapping task was identical to the procedure outlined for the single finger tapping condition. The only difference between conditions was that participants were instructed to alternate their tapping using the ‘<’ and ‘>’ buttons on the keyboard, between their index finger and middle finger, on their non-dominant hand.
Results

Recall

The proportion of words recalled was compared for all three conditions through a 3 x 6 repeated measures Analysis of Variance (ANOVA). Mauchley’s test of sphericity was met for Condition $\chi^2 (2) = 4.41, p = .11$, Serial Position $\chi^2 (14) = 19.97, p = .138$, and Condition X Serial Position interaction $\chi^2 (54) = 72.02, p = .088$. The mean proportion of words recalled per list for the pseudo-handwriting condition was .50 ($SD = .11$), .47 ($SD = .13$) for the single tap condition, and .42 ($SD = .1$) for the double tap condition. Figure 6.1 summarises the proportion of words recalled in the pseudo-handwriting condition, the single tap condition, and the double tap condition across each serial position.

A significant main effect for experimental condition was found, $F (2, 28) = 6.69, p = .004, \eta^2_p = .32$, indicating there was a difference in recall between the conditions. There was a significant effect for serial position, $F (5, 70) = 56.82, p < .001, \eta^2_p = .80$, however the interaction was not significant, $F (10, 140) = .17, p < .998, \eta^2_p = .01$. Bonferroni post hoc comparisons revealed that participants recalled significantly more words overall in the pseudo-handwriting condition compared to the double tapping condition [$MDiff = .08$, Bonferroni 95% CI: .02, .13]. There was no significant difference between the pseudo-handwriting condition and the single tap condition [$MDiff = .03$, Bonferroni 95% CI: -.01, .07]; or between the single tap and double tap conditions [$MDiff = .05$, Bonferroni 95% CI: -.02, .11]. An analysis of simple effects was conducted using Bonferroni adjusted linear contrasts to determine at which serial position the differences occurred. However, no significant difference between conditions occurred at any of the serial positions, the results of the F tests are presented in Table 6.1.
Figure 6.1. Mean word recall at each serial position as a proportion of correct responses for participants during the pseudo-handwriting, single tap, and double tap conditions. Error bars represent standard errors. Points are offset horizontally so that error bars are visible.
Table 6.1.

*Linear Contrast Results for Differences in the proportion of words recalled at Serial positions (SP) 1 to 6.*

<table>
<thead>
<tr>
<th>SP</th>
<th>Comparison</th>
<th>df</th>
<th>F</th>
<th>p</th>
<th>95% CI[Lower, Upper]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PH = ST</td>
<td>1, 14</td>
<td>0.09</td>
<td>.769</td>
<td>-.10, .13</td>
</tr>
<tr>
<td></td>
<td>PH = DT</td>
<td>1, 14</td>
<td>1.99</td>
<td>.18</td>
<td>-.06, .18</td>
</tr>
<tr>
<td></td>
<td>ST = DT</td>
<td>1, 14</td>
<td>1.64</td>
<td>.221</td>
<td>-.06, .16</td>
</tr>
<tr>
<td>2</td>
<td>PH = ST</td>
<td>1, 14</td>
<td>0.11</td>
<td>.745</td>
<td>-.07, .09</td>
</tr>
<tr>
<td></td>
<td>PH = DT</td>
<td>1, 14</td>
<td>4.39</td>
<td>.055</td>
<td>-.02, .17</td>
</tr>
<tr>
<td></td>
<td>ST = DT</td>
<td>1, 14</td>
<td>4.60</td>
<td>.05</td>
<td>-.02, .15</td>
</tr>
<tr>
<td>3</td>
<td>PH = ST</td>
<td>1, 14</td>
<td>0.68</td>
<td>.423</td>
<td>-.10, .20</td>
</tr>
<tr>
<td></td>
<td>PH = DT</td>
<td>1, 14</td>
<td>2.00</td>
<td>.179</td>
<td>-.09, .29</td>
</tr>
<tr>
<td></td>
<td>ST = DT</td>
<td>1, 14</td>
<td>.93</td>
<td>.351</td>
<td>-.10, .20</td>
</tr>
<tr>
<td>4</td>
<td>PH = ST</td>
<td>1, 14</td>
<td>0.84</td>
<td>.375</td>
<td>-.10, .21</td>
</tr>
<tr>
<td></td>
<td>PH = DT</td>
<td>1, 14</td>
<td>2.02</td>
<td>.177</td>
<td>-.07, .21</td>
</tr>
<tr>
<td></td>
<td>ST = DT</td>
<td>1, 14</td>
<td>0.33</td>
<td>.575</td>
<td>-.07, .11</td>
</tr>
<tr>
<td>5</td>
<td>PH = ST</td>
<td>1, 14</td>
<td>1.08</td>
<td>.316</td>
<td>-.07, .17</td>
</tr>
<tr>
<td></td>
<td>PH = DT</td>
<td>1, 14</td>
<td>2.30</td>
<td>.152</td>
<td>-.05, .18</td>
</tr>
<tr>
<td></td>
<td>ST = DT</td>
<td>1, 14</td>
<td>0.16</td>
<td>.695</td>
<td>-.10, .14</td>
</tr>
<tr>
<td>6</td>
<td>PH = ST</td>
<td>1, 14</td>
<td>0.09</td>
<td>.769</td>
<td>-.12, .15</td>
</tr>
<tr>
<td></td>
<td>PH = DT</td>
<td>1, 14</td>
<td>3.03</td>
<td>.104</td>
<td>-.05, .22</td>
</tr>
<tr>
<td></td>
<td>ST = DT</td>
<td>1, 14</td>
<td>1.01</td>
<td>.332</td>
<td>-.12, .26</td>
</tr>
</tbody>
</table>

*Note. PH – Pseudo-Handwriting Condition, ST - Single Top condition, DT - Double Top Condition*

**Writing kinematics**

To test if there were differences for the handwriting kinematics between each condition a series of repeated measures ANOVAs were conducted for each kinematic variable (average stroke duration, average normalised jerk, average number of strokes, average absolute velocity, and average stroke size). Figure 6.2 summarises the mean performance for each kinematic variable for each condition.
Figure 6.2. Mean (a) average stroke duration, (b) average normalised jerk, (c) average number of strokes, (d) average stroke size, and (e) average absolute velocity during the pseudo-handwriting, single tap, and double tap conditions. Error bars represent standard errors.

A significant effect was identified for average stroke duration, $F(2, 28) = 6.27, p = .006, \eta^2_p = .31$, indicating there was a significant difference in stroke duration between the conditions. Bonferroni pairwise comparisons revealed that participants took significantly longer to complete a stroke in the double tapping condition compared to the pseudo-handwriting condition [$M_{\text{Diff}} = .05$, Bonferroni 95% CI: .01, .1]. No significant differences were found between the pseudo-handwriting and single tap condition [$M_{\text{Diff}} = .02$, Bonferroni 95% CI: -.06, .2] or between the single tap and double tap condition [$M_{\text{Diff}} = .03$, Bonferroni 95% CI: -.07, 0].
A significant effect for average normalised jerk was also found, $F(2, 28) = 5.18, p = .012, \eta^2_p = .27$, showing a significant difference between the conditions for average normalised jerk. Bonferroni pairwise comparisons revealed that participant’s average normalised jerk was significantly higher in the double tapping condition compared to the single tapping condition [$MDiff = 11.22, Bonferroni 95\% CI: 1.92, 2.53$]. This is reflective of a reduction in control and smoothness of the movement. No significant differences were found between the pseudo-handwriting and single tap condition [$MDiff = 4.21, Bonferroni 95\% CI: -6.26, 14.67$] or between the pseudo-handwriting and double tap condition [$MDiff = -7.02, Bonferroni 95\% CI: -15.90, 1.86$].

The average number of strokes also changed significantly between conditions, $F(2, 28) = 5.55, p = .009, \eta^2_p = .28$. Bonferroni pairwise comparisons revealed no significant differences between conditions. However, the difference between the pseudo-handwriting condition and the double tapping condition was close to significance [$MDiff = 7.72, p = .051, Bonferroni 95\% CI: -.04, 15.48$]. No significant differences were found between the pseudo-handwriting and single tap condition [$MDiff = 2.03, Bonferroni 95\% CI: -3.41, 7.46$] or between the single tap and double tap condition [$MDiff = 5.70, Bonferroni 95\% CI: -0.49, 11.88$].

There was a significant change in the average absolute velocity between conditions $F(2, 28) = 3.76, p = .036, \eta^2_p = .21$. Bonferroni pairwise comparisons revealed no significant differences between the pseudo-handwriting condition and the single tapping condition [$MDiff = .10, Bonferroni 95\% CI: -.24, .45$], the pseudo-handwriting and double tap condition [$MDiff = .37, Bonferroni 95\% CI: -.09, .82$], or between the single tap and double tap condition [$MDiff = .26, Bonferroni 95\% CI: -.04, .56$]. The average stroke size did not differ significantly between conditions $F(1.5, 21) = 1.06, p = .346, \eta^2_p = .07$. 


Tapping measure

The tapping measures (speed and deviation) were compared for the single and double tap conditions across the six serial positions through two 2 x 6 repeated measures ANOVAs. Figure 6.3 summarises the speed and deviation, in the single tap condition and the double tap condition across each serial position. Whether participants were accurate at maintaining tapping speed over time, and if the deviation between taps increased over time.

Figure 6.3  Mean tapping speed at each serial position for the single tap and double tap conditions. Error bars represent standard errors.
Figure 6.4  Mean deviation in tapping speed at each serial position for the single tap and double tap conditions. Error bars represent standard errors.

For tapping speed, Mauchly’s test showed that sphericity was violated for Serial Position, $\chi^2 (14) = 78.56, p < .001, \varepsilon = .32$, and the Condition X Serial Position interaction, $\chi^2 (14) = 56.03, p < .001, \varepsilon = .37$, the degrees of freedom were adjusted using Huynh-Feldt ($\varepsilon$) corrections. The repeated measure ANOVA revealed that there was a significant main effect between the single and double tapping conditions, $F (1, 14) = 9.35, p = .009, \eta_p^2 = .40$, with significantly faster tapping speed in the double tap condition ($M = 467.64, SD = 4.73$) compared to the single tap condition ($M = 500.18, SD = 5.74$). There was no significant effect for Serial Position, indicating the tapping speed did not change over time, $F (1.58, 22.06) = 3.07, p = .077, \eta_p^2 = .18$. However, there was a significant Condition X Serial Position
interaction, $F(1.85, 25.96) = 5.50, p = .012, \eta_p^2 = .28$, indicating that tapping speed changed differently between conditions across time (serial position).

A simple effects analysis was conducted to see if changes in tapping speed occurred across the serial positions within each condition. A repeated measures ANOVA, (Mauchly’s - $\chi^2 (14) = 86.96, p < .001, \varepsilon = .31$) revealed a significant serial position effect within the single tap condition, $F(1.53, 21.35) = 5.66, p = .016, \eta_p^2 = .29$, this indicated that the average tapping speed changed significantly across the serial position. However, as seen in Table 6.2 the pairwise comparisons showed that none of the serial positions deviated significantly from one another.

An additional one sample T-test was conducted to see if the tapping speed for the single tap and double tap conditions deviated from the target speed (500 ms). The t-tests found the double tap condition deviated significantly from the target speed at serial position 1, $t(14) = -4.25, p = .001, d = -2.27$; serial position 2, $t(14) = -4.00, p = .001, d = -2.14$; serial position 3, $t(14) = -3.44, p = .004, d = -1.84$; serial position 4, $t(14) = -2.73, p = .016, d = 1.46$; and serial position 5, $t(14) = -2.78, p = .026, d = 1.49$. The difference at serial position 6 was not statistically significant, $t(14) = -1.81, p = .091, d = -.97$. The single tap condition only deviated from the target speed significantly at serial position 1, $t(14) = -2.31, p = .037, d = -1.23$. The tapping speed did not deviate significantly from the target for serial position 2, $t(14) = -1.01, p = .33, d = .54$; serial position 3, $t(14) = -.95, p = .358, d = -.51$, serial position 4, $t(14) = -.09, p = .928, d = -.05$; serial position 5, $t(14) = .95, p = .359, d = .51$, or serial position 6, $t(14) = 1.07, p = .303, d = .57$.

For the deviation in tapping a speed, Mauchly's test showed that sphericity was violated for Serial Position, $\chi^2 (14) = , p = .036, \varepsilon = .67$, but was met for the Condition X Serial Position interaction, $\chi^2 (14) = , p = .172$, the degrees of freedom were adjusted using Huynh-Feldt (ε) corrections. The repeated measure ANOVA revealed that there was no significant main effect for the deviation in tapping speed, $F(1, 14) = .01, p = .914, \eta_p^2 = .01$. The
deviation in tapping for the double tap condition \((M = 80.55, SD = 31.82)\) was statistically similar compared to the single tap condition \((M = 79.79, SD = 33.17)\). There was a significant effect for Serial Position, indicating the deviation in tapping speed changed significantly over time, \(F(3.48, 48.71) = 18.57, p < .001, \eta_p^2 = .57\). There was also a significant Condition X Serial Position interaction, \(F(1, 14) = 3.05, p = .015, \eta_p^2 = .18\). Table 2 displays the pairwise comparisons for the deviation of tapping speed between each serial positions within each condition. As indicated in Figure 3 (b), in both conditions the deviation in tapping speed increased across serial position, with significant differences occurring between the early and late positions. However, for the single tap condition, the tapping speed was relatively stable for serial positions 1, 2, and 3 before steeply increasing whereas for the double tap condition there was a steady increase across serial positions.

Table 6.2

The mean difference for tapping speed and the deviation of tapping speed between each serial position, within the single tap and double tap conditions.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Serial Position</th>
<th>Tapping Speed</th>
<th>Deviation in Tapping Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>6.40</td>
<td>-0.32</td>
<td>5.62</td>
</tr>
<tr>
<td>2</td>
<td>15.37</td>
<td>8.97</td>
<td>23.57</td>
</tr>
<tr>
<td>3</td>
<td>33.86</td>
<td>27.47</td>
<td>27.79</td>
</tr>
<tr>
<td>4</td>
<td>39.40</td>
<td>33.00</td>
<td>33.32</td>
</tr>
<tr>
<td>Double</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>-3.59</td>
<td>8.89</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-2.71</td>
<td>0.88</td>
<td>19.40</td>
</tr>
<tr>
<td>3</td>
<td>0.74</td>
<td>4.34</td>
<td>3.45</td>
</tr>
<tr>
<td>4</td>
<td>-0.33</td>
<td>3.26</td>
<td>2.38</td>
</tr>
<tr>
<td>5</td>
<td>2.88</td>
<td>6.47</td>
<td>5.59</td>
</tr>
</tbody>
</table>

Note. Significant differences at alpha .05 are indicated with *
Discussion

The current experiment was designed to test if the mechanism causing interference in WM performance while handwriting was due to a limited attentional resource that is diverted between multiple cognitive tasks. This was achieved by incrementally increasing the demand of an attention demanding tapping task across three conditions; a pseudo-handwriting condition, pseudo-handwriting with single tap condition, and a pseudo-handwriting with double tap condition. The results of the study showed a significant reduction in verbal serial recall for the double tapping condition compared to pseudo-handwriting condition, no other differences occurred. Further inspection of the kinematics and tapping frequencies showed a similar pattern of results. In all cases, the double tapping condition displayed relatively poorer performance compared to the single tapping condition and/or the pseudo-handwriting condition for handwriting and tapping speed. There were no significant differences between the pseudo-handwriting and single tap conditions on any of the dependent variables. I argue that the reduction in performance is due to the increasing complexity of an additional tapping task. Notably, I did not demonstrate a decrease in performance between the pseudo-handwriting task and the single tapping task in any of the analyses. However, I did determine that differences occurred between the pseudo-handwriting/single tap conditions compared to the double tapping conditions across all the dependent variables (recall, kinematics, and tapping speed). The manipulated effect is, therefore, not reflective of performing a secondary task but due to the increasing complexity. The findings suggest that WM and handwriting utilise an external, common attention resource that is depleted by a complex secondary tapping task.

The pattern of recall in all three conditions shows a common serial position curve in line with previous verbal serial recall findings (e.g. Hurlstone, Hitch, & Baddeley, 2014; Logie, Della Sala, Wynn, & Baddeley, 2000; Saito, Logie, Morita, & Law, 2008; Tan & Ward, 2008). The overall pattern indicated that recall was significantly worse in the double tap condition compared to the pseudo-handwriting condition. No difference was found
between the pseudo-handwriting and single tap conditions. Nor was there a difference between the single tapping condition and the double tapping condition. This finding is consistent with Kemper et al. (2003) who only found a detrimental effect on speech performance in the complex finger-tapping task. The recall analysis suggests that by increasing the cognitive complexity of a tapping task that resources that are normally utilised for handwriting and WM are captured. I argue that an external attention resource is utilised by all cognitive demanding tasks rather than a resource confined to a specific cognitive construct such as WM or handwriting. This is also supported by a reduction in kinematic fluency when the task complexity was increased.

The trend of results in the analysis of kinematics revealed a similar pattern to what was observed between the three conditions in the recall analysis. There was no difference observed between the pseudo-handwriting condition and the single tap condition, but consistently poorer performance for the double tap condition. The results demonstrated a decrease in handwriting fluency when the double tapping task was implemented. This is consistent with Ransdell, Levy, and Kellogg (2002) who found that handwriting fluency decreased as the load of a competing WM task was increased. The results showed that during the double tapping condition the kinematics of handwriting changed significantly. Specifically, when completing the double tapping condition, the strokes took longer to complete, the control and smoothness of the movement decreased, and participants completed fewer strokes. According to the time-based resource-sharing model of working memory, resources are rapidly and constantly switched between competing tasks. However, when one task captures attention for longer periods, this prevents resource being shared with the concurrent tasks. Therefore, when participants were simultaneously completing multiple tasks (i.e., the WM, handwriting, and tapping) this prevented resources from switching back and forth to maintain optimal performance on all the tasks. As a consequence, handwriting fluency decreased to compensate for the resource demands needed to process and maintain items in
WM as well as the demands of the complex tapping task, resulting in a decrease in overall
cognitive performance.

Interestingly, a similar pattern occurred for the tapping speed in the double tap
condition. The tapping was significantly faster compared to the single tap condition and
deviated from the target tapping speed of 500 ms. There was a noticeable reduction in
handwriting fluency as well as the accuracy of the tapping speed for the double tap condition.
I argue that when attention is needed to maintain all the tasks (recall, handwriting fluency, and
tapping speed) a trade-off must be made. This results in the performance of all tasks
deteriorating in order to maintain a minimal level of efficiency across them all. However, this
effect was only elicited when the complexity of the tapping task was increased.

Chapters 3 and 4 identified that handwriting reduced verbal WM performance when
performed concurrently. The present findings support this and further emphasise that
handwriting and WM share a common resource. However, it is only when adding a complex
attention-demanding task that an effect is elicited. The attentional demand to produce the
single taps was not challenging enough for performance to deviate significantly from the
pseudo-handwriting condition. Nevertheless, by increasing the complexity of the tapping task
I successfully reduced performance for recall, handwriting fluency, and tapping speed. From
this, I can conclude that the reduction in performance is not due to a dual task as such, but due
to a reduction in the availability of resources between the conditions, due to task complexity.

The results of this study lend support for the concept put forward by Barrouillet and
Camos (2007). In the authors initial paper (e.g. Barrouillet & Camos, 2007), they suggested
that rather than conceptualising the TBRS model as a central bottleneck, whereby only one
task can be completed at a time, that consideration should be given to the possibility that
attention capture may be more accurate in explaining the model. From the results, I have
shown a robust finding for attention capture within the framework of the TBRS model. The
assumption that an external attention resource is utilised by all cognitive demanding tasks
rather than a resource confined to a specific cognitive construct was supported by the findings. This also lends support to cognitive-neurological models of WM (e.g., Postle, 2006).

The findings also strengthen cognitive-neurological models of attention, WM, and handwriting (Brown, Collier, & Night, 2013; Clarke, Browning, Hammond, Notebaert, & MacLeod, 2014; Kellogg, 1996; Postle, 2006; Schneider, Schote, Meyer, & Frings, 2014). That is, attention is most likely governed by the DLPFC. Any cognitive task that needs attention requires the DLPFC to focus on the neurological region needed to perform that task. In these tasks, the DLPFC would need to focus attention on the left posterior perisylvian areas for verbal WM (e.g., speech perception; Postle, 2006). As I am only concerned with motor component of handwriting, it is likely that the primary motor and sensorimotor cortex, supplementary motor area were activated (Planton, Jucla, Roux, & Démonet, 2013), and the right motor cortex and left cerebellum would be activated while finger tapping with the left hand (Nyberg, Eriksson, Larsson, & Marklund, 2006). As performance was only reduced when performing the double tapping task, this would suggest that the DLPFC became overloaded when the complexity was increased. This could be due to a greater focus of attention on the specific neurological regions needed to produce double taps, limiting the DLPFCs ability to devote or switch resources back to maintaining words and producing fluent handwriting movements. To confirm this assumption, neurological studies incorporating fMRI could identify the neural correlates of the allocation of attention between WM and non-WM related tasks.

In terms of the two tapping tasks, it could be that the single tapping task can be completed more automatically. This is evident in the accurate tapping speed and non-significant differences in stroke duration and jerk comparable to the pseudo-handwriting condition. The task did not significantly capture attention for relatively lengthy periods and allowed attention to be easily switched back to processing and maintenance. Conversely, the increased complexity during the double tapping condition meant that attention was captured
for relatively lengthier periods compared to the single tapping condition. This is evident in the quicker, less accurate tapping speed and the production of significantly more taps, in addition to a reduction in handwriting performance. The significantly longer stroke duration also suggests that more time was spent producing strokes compared to the pseudo-handwriting condition. Taken together, it appears that when increasing the complexity of the tapping task participants spent more time focusing resources on producing the tap sequence and conducting strokes. Consequently, attention was captured for a relatively longer period preventing attention to be switched back to maintenance and processing of items within WM.

The overall implications of this study lend further support for a central pool of attentional resources that are utilised by cognitive demanding tasks (Conway & Engle, 1996; Kane, Bleckley, Conway, & Engle, 2001; Kane et al., 2004; Morey & Cowan, 2004; Morey, Cowan, Morey, & Rouder, 2011; Sweller, Ayres, & Kalyuga, 2011; Unsworth & Spillers, 2010). Furthermore, the findings provide evidence in support of the TBRS model (Barrouillet & Camos, 2007; Barrouillet, Bernardin, & Camos, 2004). This is supported by the reduction in the proportion of words recalled between the pseudo-handwriting and tapping conditions. Specifically, the difference between the pseudo-handwriting and double tapping task indicates that that the additional attentional load is reducing performance. We can also see that by incrementally increasing the complexity of task the efficiency, allocation, and availability of resources changes. By doing this we can achieve a significant decrease in performance across multiple cognitive processes.

This study has provided strong evidence that that the mechanism contributing to a reduction in WM while handwriting can be attributed to a central pool of attentional resources that are allocated and switched between tasks and processes. In the context of Barrouillet and Camos’ (2007) TBRS model, I can confirm their suggestion that attention capture may explain differences in performance between competing tasks rather than the existence of a central bottleneck. If a central bottleneck existed, it would be expected that a decrease in
performance would also occur in the single tapping condition, as hypothesised. The current study supports previous literature identifying that writing and WM both require a common pool of resources. Additionally, even when the availability of resources is captured by tasks that do not utilise WM there is a reduction in available resources for processing, maintenance, and retrieval. Further consideration should be given to identifying whether attention is a governing system of cognition rather than conceptualising it as a construct confined to different cognitive processes such as WM.

Over several chapters I have been developing the argument that performance on the verbal serial recall task depends on how long attention is captured and held by a secondary task, and that it is the movement aspects of the currently studied secondary tasks that are capturing attention. If this is correct, then a secondary motor task unrelated to handwriting and without a phonological component that continuously captures attention should have a larger detrimental effect on performance than a task that intermittently captures attention then releases it for other processes. This will be examined in chapter 7.
Chapter 7 – Fine motor movements while drawing reduce verbal serial recall.

This chapter is adapted from the publication:

The findings of my previous chapters have identified that handwriting while simultaneously listening to lists of words significantly reduces performances on the verbal WM tasks compared to just listening. Further to this, we have provided robust evidence that it is the movements used to produce the handwriting and pseudo-handwriting that are responsible for most of the interference that is observed when a concurrent verbal serial recall task is performed. The experiment detailed in this chapter aims to identify if performing fine motor movements which are unrelated to handwriting simultaneously while listening to words will result in an interference of verbal WM performance. The experiment will also aim to identify if different types of movements (continuous or discrete) will have differing effects on verbal recall. That is, movement tasks that either capture and hold attentional resources, or capture then release attentional resources. The fundamentals and rationale for conducting this experiment are elaborated below.

It is important to note that complex tasks can be cognitively demanding (utilising resources) and can affect storage processing (Bancroft, Hockley, & Servos, 2014). In this context, cognitively demanding refers to the processes required to generate ideas, translate sounds into letters (phoneme to grapheme conversion), form sentences, edit, spell, and produce fine motor movements, all of which demand WM resources. Together, these processes strain WM resources and emphasise the cognitively demanding nature of handwriting. For example, Bancroft et al. (2014) defined complexity as the number of dimensions that are required to process a stimulus within WM. For example, a stimulus with a single dimension may include tasks that require participants to decide if two images belong to the same category. This response does not require the participant to remember all the peripheral information associated with the stimulus (which could be quite complex) but only the category (which is one-dimensional).
Bancroft et al. (2014) found that at a neurological level, the complexity and dimensionality of a stimulus influenced how information was processed, and how well it would be remembered. These findings should be kept in mind when developing to-be-remembered stimuli and secondary tasks to ensure consistency across trials and conditions. Conversely, the TBRS model suggests complexity does not always equal greater cognitive load (Barrouillet & Camos, 2007). Instead, it proposes that performance is dependent on the length of time needed to process a multi-dimensional stimulus, rather than its inherent complexity (Barrouillet & Camos, 2007; Kahneman, 1973). That is, the model states that WM performance deterioration is not solely determined by task complexity. Secondary tasks that capture attention for long periods will prevent the switching of resources back to memory processing and maintenance, whether the secondary task is complex or not.

The current study will investigate whether secondary tasks (with different performance demands) that require significant attentional resources will reduce recall on a verbal WM task. A detrimental effect of having to switch resources between tasks has been identified by Garavan (1998) and Oberauer (2003). Their participants had to switch attention between separate WM tasks such as maintaining two independent running counts (Garavan, 1998). They found that participants were only able to attend to a single task at any given time. Furthermore, recall was reduced when the secondary task captured attention for longer periods. This and other literature (e.g. Barrouillet & Camos, 2007) shows that secondary tasks that require executive attention can interfere with WM processing and maintenance. However, it has not identified to what extent attention needs to be captured for WM performance to be affected. Further to this, identifying whether tasks that place different patterns of attentional demands will have varying effects on a verbal serial recall task is yet to be investigated. Finally, previous research (Garavan, 1998; Oberauer, 2003) only used memory related secondary tasks. Tasks that are not primarily memory related but are cognitively demanding should also be investigated.
One task that has been identified as cognitively demanding is the production of fine motor movements (Albinet, Tomporowski, & Beasman, 2006) while writing (Peverly, Garner, & Vekaria, 2013; Tucha et al., 2006) and drawing for children (Blank, Miller, von Voss, & von Kries, 1999) and adults (Tucha, Mecklinger, Walitza, & Lange, 2006; Tucha, Walitza, et al., 2006). The cognitive demand associated with producing drawings is not associated with the novelty or familiarity of the shapes as such, but extends from inherent characteristics of the required movement, such as the number of strokes and the biomechanical and coordination demands. (Braswell & Rosengren, 2000). This was demonstrated by Braswell & Rosengren (2000) using simple shapes (circle, triangle, square and asterix) and complex drawings (house, face, sun) which were essentially combinations of the simple shapes. However, it is not known how different types of drawing movements require differing levels of attention, or patterns of attention to complete. It would be expected that movements that capture attention for longer periods, regardless of shape complexity or novelty, should reduce the availability of resources for concurrent cognitive tasks. The current study investigates whether performing a cognitively demanding drawing task reduces performance on a verbal WM (serial recall) task. It also examines whether a continuous movement (that requires sustained attention) will have a greater impact than a task involving discrete movements (where attention can be released between movements).

The effect of different drawing movements on verbal serial recall was examined via three tasks, in which participants had to: (1) simply listen to word lists, then verbally recall them (with no secondary task); (2) listen to word lists while simultaneously producing a continuous movement, then verbally recalling the words, and finally; (3) listen to word lists while performing discrete movements, then verbally recall them. I chose two types of movements with different coordination requirements. These were continuous movements, which require sustained attention as the participant performs the movement continuously without stopping the stylus (in this case, circle drawing), and discrete movements, which
require the stylus to stop and change direction after each stroke, allowing attention to be released between strokes (in this case, drawing stars made up of a series of straight lines).

Although the circles are drawn with a continuous movement, the movement can be considered as a series of curved (semicircular) strokes, where the stylus slows down marginally at opposite sides of the circle due to biomechanical and coordination constraints of the hand/arm/shoulder system (Dounskaia, Ketcham, & Stelmach, 2002; Dounskaia, Van Gemmert, & Stelmach, 2000; Longstaff et al., 2003). As such, both the discrete and continuous movements are made up of a series of strokes. The two shapes are also consistent with the simple shapes used in Braswell and Rosengren (2000) and would suggest that the inherent complexity of the shapes is not different. Therefore, I am only measuring the effect of the drawing movements on recall (and associated attentional requirements), with stimulus complexity controlled for.

Firstly, to see if there is an overall effect of a secondary movement task (regardless of the nature of the task) the discrete and continuous conditions will be collapsed together and the overall recall results compared to the listening task. It is expected that recall will be worse for the combined movement conditions compared to the listening condition where there can be a sustained focus of resources on processing and maintenance. Secondly, I investigated whether performance differed due to the different types of movements (continuous and discrete). It is expected that consistent with the TBRS model (Barrouillet & Camos, 2007) the continuous movement (with no pauses) will result in poorer recall compared to the discrete movement, as it requires sustained attention throughout to maintain accurate, curvilinear angular movements. The discrete task will not be as disruptive to performance as it involves movements that are straight, with single angular changes between strokes where the movement can briefly pause, allowing attention to be diverted to processing and maintenance.
I will also investigate if recall differs at individual serial positions between the listening, discrete, and continuous conditions. As additional words in the list are required to be processed and maintained, the resource demands change. The typical pattern of recall in verbal serial recall experiments is that there are high levels of recall at the early serial positions, dropping during the middle serial positions where task demands are greatest, and a slight increase in recall for the final positions (Hurlstone et al., 2014; Logie et al., 2000; Oberauer, 2003; Saito et al., 2008; Tan & Ward, 2008). By comparing how performance between tasks changes over time as the task progresses, we can gain further insight into the allocation of resources between tasks. To investigate how the differing movements are being performed, comparisons between the kinematics (speed, size, duration, normalised jerk, number of strokes, and movement pauses) will also be made to help explain any differences that may occur between the conditions.

**Methods**

**Participants**

The experiment included 15 voluntary participants from the university and the general public (Females, n= 10; Males, n= 6; mean age = 30.5 years).

**Apparatus**

The experiment was conducted in a lab set up with a personal computer (screen resolution, 1680 x 1050) and a Wacom (Intuos3, 12”x19”, model PTZ-1231W) digital writing pad and pen (stylus) to record the movements of participants. MovAlyzeR (Neuroscript LLC, USA) displayed the movements on a computer screen and recorded the pen movements. Participants listened to a pre-recorded list of words spoken by the researcher (through headphones) also presented using MovAlyzeR.

I would also look to outline that in this experiment we revert to using the WACOM tablet, instead of the Microsoft surface pro. As briefly mentioned in chapter 4, there were no
meaningful differences in the analysis between these two devices. The WACOM tablet allows
the participant to see there continuous drawing trace without impediment which would occur
if the hand was covering the visual representation on the Microsoft surface Pro screen. That
is, when using the Wacom tablet, the pen trace of the participants drawing is shown on the
screen behind the tablet. Due to the continuous or ongoing discrete motions required, it is
much easier for participants to maintain a constant physical motion (or repetitive discrete
movements) while gaining unobstructed visual feedback.

In addition to this, in chapter 4 we found that there were only minor observable
differences (if any) between performance when using the Wacom tablet or the ThinkPad. It is
also very common in this field to record and display movements like this.

The shape used in the continuous condition was a circle with a diameter of 10 cm (i.e.
a circumference of 31.4 cm which equates to an expected stroke size of 15.7 cm). The shape
in the discrete condition was a five-pointed star with a stroke size of 4.5 cm. The movements
for the star are discrete because the sharp changes of direction at the points necessitate a
slowing down (stopping) at the end of each stroke. The target shapes and drawing movements
were displayed on the computer screen. To maintain uniformity and a degree of similarity in
the size of the shapes, the global width/diameter of the stimuli were the same, that is, the star
fits within the circle (Figure 7.1).
Procedure

The procedure for the listening condition was similar to the listening conditions in the previous chapters. Participants listened to lists of 6 words before recalling them aloud, in the same order as they were presented. The continuous and discrete movement conditions procedure was similar to the pseudo-handwriting conditions in the previous chapters. The listening with continuous movement required participants to draw continuous revolutions of a circle as they listened to word lists, before recalling them. The discrete drawing condition asked participants to draw a five-pointed star while listening to the word lists, before recalling them. When completing the star, they were to keep drawing the star shape over the top of the star until they heard all the words. In both drawing conditions, the target shape was displayed and participants were asked to match the size and shape, drawing as quickly and accurately as possible. Participants ceased drawing when they reached the recall phase and were prompted to continue after recall had been completed.
**Results**

*Word recall*

To explore the differences in the overall proportion of words recalled with or without a concurrent movement task, the continuous and discrete movement conditions were collapsed together (the “movement condition”) and compared to the listening condition. The overall proportion of words recalled was compared using Bonferroni adjusted linear contrasts, i.e. a comparison was made with two levels of condition (listening and movement). The results showed a significantly higher proportion of word recall in the listening condition compared to the movement condition, $F(1, 14) = 12.62, p = .003, 95\% \text{ CI} [.022–.09]$. In order to see if differences between the listening and movement conditions also occurred at individual serial positions, further Bonferroni adjusted linear contrasts were conducted. This revealed significant differences at serial positions 3, $F(1, 14) = 8.99, p = .019 [95\% \text{ CI}: .03–.18]$ and 4, $F(1, 14) = 1.44, p = .01 [95\% \text{ CI}: .04–.21]$ between the listening condition and movement condition.

To investigate how recall for the movement conditions differed individually from each other as well as the listening condition, a $3 \times 6$ repeated measures ANOVA was conducted, with three levels of condition (listening, continuous, and discrete) and six levels of recall (serial positions 1–6). Assumptions of normality were met for all three conditions (all Shapiro Wilks tests reported a $p > .50$). Mauchly’s test showed that sphericity was met for Condition, $\chi^2(2) = 1.83, p = .402$, but was violated for Serial Position, $\chi^2(14) = 31.86, p = .005, \varepsilon = .71$, and the Condition × Serial Position interaction, $\chi^2(54) = 76.88, p = .042, \varepsilon = .76$, the degrees of freedom were adjusted using Huynh-Feldt ($\varepsilon$) corrections. Figure 7.2 summarises the mean proportion of words recalled in the listening condition, the continuous movement condition, and the discrete movement condition.

The analysis revealed a significant main effect for Condition, $F(2, 28) = 5.37, p = .011$, $\eta^2_p = .28$, indicating there was a difference in recall between the listening, continuous, and discrete conditions. There was a significant effect for Serial Position, $F(3.57, 49.92) = 45.67,$
$p < .001$, $\eta^2_p = .77$, and the Condition X Serial Position interaction, $F (7.63, 106.76) = 2.74$, $p = .01$, $\eta^2_p = .16$. Post hoc comparisons revealed that participants recalled significantly more words overall in the listening condition compared to the continuous condition [MDiff = .06, 95% CI: .019, .11]. There was no significant overall difference between the listening condition and the discrete condition or between continuous and discrete conditions.

Since the Condition $\times$ Serial Position interaction was significant, an analysis of simple effects was conducted to determine at which serial position the differences occurred. The results of the linear contrasts are presented in Table 7.1. A series of linear contrasts revealed a significant difference at serial position 3 and 4 between the listening condition and both the continuous condition and the listening and discrete condition. There was also a significant difference at serial position 5 between the listening and continuous conditions, and the continuous and discrete conditions.
Figure 7.2  Mean proportion of correct word recall at each serial position for participants during the listening, continuous movement (circle), and discrete movement (star) conditions. Error bars represent standard errors. Points are offset horizontally so that error bars are visible.
Table 7.1

Linear Contrast Results for Differences in the proportion of words recalled at Serial positions (SP) 1 to 6.

<table>
<thead>
<tr>
<th>SP</th>
<th>Variables</th>
<th>df</th>
<th>F</th>
<th>p</th>
<th>95% CI[Lower, Upper]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L = C</td>
<td>1, 14</td>
<td>.06</td>
<td>.81</td>
<td>-.080, .067</td>
</tr>
<tr>
<td></td>
<td>L = D</td>
<td>1, 14</td>
<td>2.11</td>
<td>.168</td>
<td>-.034, .111</td>
</tr>
<tr>
<td></td>
<td>D = C</td>
<td>1, 14</td>
<td>1.91</td>
<td>.189</td>
<td>-.044, .135</td>
</tr>
<tr>
<td>2</td>
<td>L = C</td>
<td>1, 14</td>
<td>.72</td>
<td>.410</td>
<td>-.066, .126</td>
</tr>
<tr>
<td></td>
<td>L = D</td>
<td>1, 14</td>
<td>.58</td>
<td>.459</td>
<td>-.089, .159</td>
</tr>
<tr>
<td></td>
<td>D = C</td>
<td>1, 14</td>
<td>.01</td>
<td>.922</td>
<td>-.140, .149</td>
</tr>
<tr>
<td>3</td>
<td>L &gt; C</td>
<td>1, 14</td>
<td>6.42</td>
<td>.024*</td>
<td>-.006, .175</td>
</tr>
<tr>
<td></td>
<td>L &gt; D</td>
<td>1, 14</td>
<td>7.89</td>
<td>.014*</td>
<td>.004, .252</td>
</tr>
<tr>
<td></td>
<td>D = C</td>
<td>1, 14</td>
<td>1.38</td>
<td>.260</td>
<td>-.057, .143</td>
</tr>
<tr>
<td>4</td>
<td>L &gt; C</td>
<td>1, 14</td>
<td>11.71</td>
<td>.004**</td>
<td>.028, .240</td>
</tr>
<tr>
<td></td>
<td>L &gt; D</td>
<td>1, 14</td>
<td>6.43</td>
<td>.024*</td>
<td>-.009, .261</td>
</tr>
<tr>
<td></td>
<td>D = C</td>
<td>1, 14</td>
<td>.04</td>
<td>.844</td>
<td>-.114, .098</td>
</tr>
<tr>
<td>5</td>
<td>L &gt; C</td>
<td>1, 14</td>
<td>9.51</td>
<td>.008**</td>
<td>.013, .209</td>
</tr>
<tr>
<td></td>
<td>L = D</td>
<td>1, 14</td>
<td>.68</td>
<td>.423</td>
<td>-.081, .151</td>
</tr>
<tr>
<td></td>
<td>D &gt; C</td>
<td>1, 14</td>
<td>8.65</td>
<td>.011*</td>
<td>-.146, -.006</td>
</tr>
<tr>
<td>6</td>
<td>L = C</td>
<td>1, 14</td>
<td>.51</td>
<td>.487</td>
<td>-.090, .154</td>
</tr>
<tr>
<td></td>
<td>L = D</td>
<td>1, 14</td>
<td>3.11</td>
<td>.100</td>
<td>-.147, .031</td>
</tr>
<tr>
<td></td>
<td>D = C</td>
<td>1, 14</td>
<td>4.03</td>
<td>.064</td>
<td>-.212, .032</td>
</tr>
</tbody>
</table>

Note: L – Listening Condition; C – Continuous condition; D – Discrete condition

* p < .05
** p < .01

Order errors were analysed as the proportion of order errors in each condition. A repeated measures ANOVA revealed no significant difference between the proportion of order errors made in each condition (Listening $M = .12, SD = .07$; Continuous, $M = .14, SD = .08$; Discrete $M = .14, SD = .1$).

Movement characteristics in encoding phase

To provide insight into how the movements in the continuous and discrete condition were being performed, comparisons between the movement kinematics were made using
paired sample t-tests. The means and standard deviations for each kinematic variable are displayed in Table 7.2.

A one sample t-test revealed that the average stroke size did not differ significantly from the target stroke size (target = 15.7, actual = 14.94, SD = 2.4) for the continuous condition, $t(14) = -1.23, p = .239, d = -0.45, 95\% CI [-2.09, 0.57]$, but was slightly smaller than target size (target = 4.5, actual = 4.13, SD = 0.89) for the discrete condition, $t(14) = -3.75, p = .002, d = -1.37, 95\% CI [-1.36, -0.37]$. The results show that the stroke size was significantly greater in the continuous condition than the discrete condition, $t(14) = 17.50, p < .001, d = 5.96, 95\% CI [9.48, 12.12]$. Participants' speed was significantly higher in the continuous condition compared to the discrete condition, $t(14) = 5.72, p < .001, d = 1.81, 95\% CI [9.45, 2.79]$. There were no significant differences found between the two movement conditions for average stroke duration, average normalised jerk, or average number of strokes. Therefore, the strokes in the continuous condition were both larger and quicker but the duration and number of strokes produced did not differ i.e. participants were drawing the bigger strokes faster, maintaining stroke duration.
Table 7.2

*Means and standard deviations for the kinematics (duration, size, absolute velocity, normalised jerk, and number of strokes) for the continuous and discrete drawing conditions.*

<table>
<thead>
<tr>
<th>Condition</th>
<th>Duration (s)</th>
<th>Size (cm)</th>
<th>Absolute Velocity (cm/s)</th>
<th>Normalised Jerk</th>
<th>Number of Strokes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$</td>
<td>$SD$</td>
<td>$M$</td>
<td>$SD$</td>
<td>$M$</td>
</tr>
<tr>
<td>Continuous</td>
<td>.98</td>
<td>.18</td>
<td>14.94</td>
<td>2.40</td>
<td>22.80</td>
</tr>
<tr>
<td>Discrete</td>
<td>.84</td>
<td>.17</td>
<td>4.13</td>
<td>.89</td>
<td>7.68</td>
</tr>
</tbody>
</table>

*Pauses in movement*

The number of times the participants paused their movements during each word list was significantly greater for the discrete condition ($M = 2.40$, $SD = 1.04$) compared to the continuous condition ($M = .08$, $SD = .09$), $t (14) = −8.17$, $p < .001$, $d = −3.16$, 95% CI $[−2.93, −1.71]$. This indicated that on average participants were producing close to 0 pauses in the continuous condition, but about 2.4 pauses per list in the discrete condition. The average total duration of the pauses per word list for the continuous condition ($M = 10$ ms, $SD = 20$ ms) was significantly less than the discrete condition ($M = 430$ ms, $SD = 230$ ms), $t (14) = −6.75$, $p = .001$, $d = −2.54$, 95% CI $[−2.93, −1.71]$. That is, the participants paused for close to 0 ms per word list in the continuous condition and about 430 ms in the discrete condition. A simple linear regression was conducted to test if the pauses in movement could significantly predict the proportion of words recalled for the continuous and discrete conditions. A significant regression model was identified for the discrete condition, indicating that the duration of pauses accounted for 61.5% of the variance in recall, $R^2 = .62$, $F (1, 14) = 2.75$, $p = .001$. This identifies that as the duration of pauses increases, the proportion of words recalled also increases (see Figure 7.3), $B = .46$, CI 95% $[.24−.67]$, $\beta = .78$, $t = 4.56$, $p = .001$. The regression model for the pauses in movement in the continuous condition showed that the
duration of pauses accounted for almost no variance in recall, $R^2 < .01, F (1, 14) = .02, p = .885, B = -.22, CI 95\% [-3.41–2.97], \beta = -.04, t = -.15, p = .885$.

**Discussion**

The current experiment was conducted to assess if cognitively demanding fine-motor movement tasks would reduce performance on a concurrent verbal WM (serial recall) task; and if the type of movement (continuous vs discrete) would have differential effects on performance related to the attention and resource demands of the movements. By collapsing the two movement conditions together, I identified that the production of fine-motor movements reduced verbal serial recall performance compared to the listening condition. I further identified that the differences between the listening condition and the combined
movement conditions occurred at serial positions 3 and 4. When looking at the movement conditions independently I found that in line with my predictions, overall recall was significantly worse for the continuous movement condition compared to the listening condition. While there was no overall difference between the discrete condition and either the listening or continuous conditions, differences in recall did occur between conditions at individual serial positions. Firstly, recall performance was better for the listening condition than the continuous condition at serial positions 3, 4, and 5. Recall while listening was also better compared to the discrete condition at serial positions 3 and 4. Recall in the discrete condition was better compared to the continuous condition at serial position 5. These finding support the hypothesis and provides evidence for TBRS model (Barrouillet & Camos, 2007). I argue that the continuous condition captured attention for a lengthier period relative to the discrete condition, preventing the switching of resources to processing and maintaining the words.

The general pattern of recall across serial positions for all conditions was the same as previous experiments (Hurlstone et al., 2014; Logie et al., 2000; Saito et al., 2008; Tan & Ward, 2008, Tindle & Longstaff, 2015, 2016a, 2016b) with a typical primacy and recency effect occurring, with a flattening during the middle serial positions. The more fine-grained analysis of recall at each serial position identified differences between all three conditions at some of the serial positions, providing additional insight into how recall was affected. There were differences between the continuous condition and the listening condition at serial positions 3, 4, and 5. This reinforces the overall recall findings and provides further evidence that the continuous condition was preventing resources being switched back to processing and maintenance for long periods of time, consistent with the TBRS model.

For the discrete movements, there are differences at serial positions 3 and 4 compared to the listening condition. Despite no difference in overall recall between the discrete and listening conditions, there is some effect associated with the discrete movements localised to
these mid serial positions. At serial position 5, recall in the discrete condition was significantly better compared to the continuous condition and the same as the listening condition. This is indicative of the differences in how the two movement tasks are performed, showing that the continuous condition is much more resource demanding and diverts resources away from processing and maintenance for a longer period. To further address the robustness of the TBRS model of WM, I recommend that further investigation of the effect of discrete fine motor movements on WM should be conducted. For example, the duration (or size) of the discrete movement could be manipulated to see if that changes how attention is captured, or if having more opportunities to pause and switch resources improves recall, and fewer opportunities reduces recall. This will provide further evidence for the notion that WM performance is dependent on how well resources can switch between processing and maintenance, when a secondary task is completed simultaneously. However, this is beyond the scope of my thesis.

It is interesting that the difference between the conditions was confined to the middle serial positions, with the primacy and recency items being unaffected by the secondary movement tasks. However, in the context of the TBRS model and Cowan's (2001, 2010) suggestion that WM is limited to approximately 3–5 item chunks, this finding is unsurprising. During all three tasks, resources are at their maximum availability at serial position 1, this ensures efficient encoding and maintenance of that item for a relatively longer period than the following items (serial positions 2–5). The recency items experience a slight increase in recall compared to the middle positions. This is likely due to short term memory's ability to maintain recent items relatively well for immediate recall (Pattamadilok, Lafontaine, Morais, & Kolinsky, 2010; Saito et al., 2008; Spurgeon, Ward, & Matthews, 2014). This effect is maintained even when a secondary drawing task is performed, and I argue that this is due to the nature of the task. That is, after the presentation of the final word, participants' drawing ceases. This means that no further interference to short term memory occurs, enabling the
same level of efficiency for the recency items as experienced in the listening condition. The
effect of the secondary task on the primacy items is minimal due to the abundance of
resources. Conversely, the recency items benefit because there is little interference from the
secondary task after the presentation of the final word.

The TBRS model (Barrouillet & Camos, 2007) explains why the type of movement
being produced is having differing effects on recall. There was a significant reduction in word
recall when producing the continuous movement. While the inherent complexity of the circle
and star shapes is similar (Braswell & Rosengren, 2000), the type of movements that were
required to produce the circle utilised resources for an extended and sustained period with no
pauses. The resources were continually captured to maintain the speed, shape (requiring an
ongoing change in the angle of the movement), and size of the circle, without stopping. This
in turn, prevented resources switching back to processing and maintenance for long periods of
time, resulting in poorer recall compared to the listening condition at serial positions 3, 4, and
5 and the discrete condition at serial position 5.

For the discrete (star) condition, participants only needed to make a series of straight
movements. There were single changes in direction at the end of each stroke compared to
ongoing changes in the angle of movement required to draw the circle. The straight lines did
not require constant attention to perform after the initiation of each movement, and allowed
more efficient switching of resources back to processing and maintenance. This is further
supported by the finding that participants included brief pauses during the discrete condition.
Additionally, a significant regression analysis provides further evidence, that not only do
pauses in movement increase recall, but as the duration of those movements increases, so too
does the proportion of words recalled. A compelling argument can be made that the additional
pauses in movement contributed to greater recall compared to the continuous movement by
allowing a brief window where resources could switch back to processing and maintenance. I
have demonstrated that when resources have the opportunity to be sustained for relatively
longer periods on processing and maintenance, more words can be remembered. This also explains why overall recall for the discrete condition did not differ from the listening condition, as resources had the opportunity to switch back to processing and maintenance.

This explanation fits well with the model outlined by Barrouillet and Camos (2007) and the suggestion that the complexity of the task does not necessarily result in greater cognitive load, but the task that captures attention for a lengthier period will result in a greater reduction in WM performance. In the context of these findings, while the shapes do not appear to be more inherently complex (Braswell & Rosengren, 2000), the movements needed to produce the circle are more resource demanding. This explanation also fits well with the model outlined by Barrouillet and Camos (2007) and the suggestion that the complexity of the task does not necessarily result in greater cognitive load, but the task that captures attention for longer periods will result in a greater reduction in WM performance. The different pattern of results for the discrete and continuous conditions show that it is not just performing a secondary movement task that leads to performance deterioration in a concurrent WM task, but it is how the participants were completing the movement task that is important. The analysis of kinematics between the discrete and continuous conditions revealed that participants differed significantly on the size and speed of their strokes, which could be expected given the task requirements. However, the analysis showed duration did not differ. This is interesting as it indicates participants were taking the same amount of time to complete an average stroke size of 4.13 cm in the discrete condition compared to an average stroke size of 14.94 cm in the continuous condition, resulting in the speed of movement being significantly faster in the continuous condition compared to the discrete condition.

It is clear from the analysis that the movements used to draw the two shapes were statistically different, requiring different strategies and movement dynamics to complete. These differences are reflective of the differences in recall and identify an explanation for these results. The continuous movement is more time and attention demanding than the
discrete movement, necessitating an additional, sustained demand for resources. The findings from the analysis of the kinematics are consistent with the pattern of recall and further emphasises my interpretation within Barrouillet and Camos’ (2007) TBRS model. That is, in the continuous condition participants were constantly changing the direction of movement and covering more spatial area in the same amount of time while maintaining a significantly higher velocity throughout. This required significantly more resources to be continually devoted to the movements preventing the switching of resources back to processing and maintenance. The straight moments, shorter stroke sizes, slower movement speed, and increased frequency and duration of pauses in the discrete condition, suggests that participants' movements were not as demanding and allowed resources to be switched back to processing and maintenance much more effectively. To further test the effect of continuous and discrete movements on WM performance, utilising straight lines with different movement characteristics may further strengthen the current findings. For example, a future study could compare WM performance across two tasks: one involving a discrete straight movement that requires participants to move back and forth with pauses between targets. Second, a continuous series of straight movements that requires participants to move back and forth between targets without pausing. The speed and size of these movements could also be manipulated.

**Conclusion**

I conclude that secondary tasks involving fine motor movements reduce WM performance. However, it is not merely performing a movement task, but the type of movement and pattern of attentional demands that is important in determining how resources are diverted. The findings provide support for recent models of WM showing how resources are shared and diverted to secondary tasks and prevent processing and maintenance within WM (Barrouillet & Camos, 2007).
In the previous chapters I found that handwriting and pseudo-handwriting reduce WM performance. The results suggested that this effect was largely due to the motor component with little additional change in performance due to the verbal component of handwriting. To further investigate the concept that fine motor movements reduce WM performance the above study was conducted. This has further emphasised that fine motor movements do reduce WM performance, but further indicate that continuous movements capture attention for longer periods compared to discrete movements. This provides robust evidence in favour of the TBRS model. The evidence I have provided in this thesis suggests that WM performance is subject to time-related decay. In the following chapter I investigate how the allocation of time to specific processes across a serial position curve contributes to the pattern of results found in the previous experiments I have presented in the thesis and previous verbal serial recall studies within the literature.
Chapter 8 – Predicting the pattern for verbal serial recall: The proportion of time for decay, activation, and rehearsal.
In the previous chapters I have identified that handwriting and other movement tasks interfere with WM processes. I have also consistently demonstrated a typical immediate verbal serial recall pattern (see Figure 8.1). In the framework of the TBRS model, I suggest that deterioration is due to attention being captured for lengthy durations. As the model is concerned with time based processes related to processing/encoding, maintenance, and the decay of information, this chapter uses a few simple assumptions centred on these as a starting point to begin developing a time based mathematical model. This is presented as an attempt to explain the typical serial position curves for verbal serial recall tasks and the results presented in my thesis.

Verbal serial recall typically refers to the ability to immediately recall a list of words, numbers, or letters in the order they were presented after hearing them. The limits and underlying mechanisms of serial recall have been investigated previously, with some suggestions that serial recall is limited by specialised short-term memory systems (e.g. the multi-component model of WM Baddeley, 2000; Baddeley & Hitch, 1974). While alternative models suggest that short term memory is limited by the mechanisms needed to process speech and language (Allen & Hulme, 2006).

Essentially, previous models have focussed on aspects of the stimuli and the mechanisms needed to process, encode, manipulate, and transform language in order for it to be remembered in a serial order. Factors such as word length, familiarity, frequency, and similarity have been known to affect how well words will be remembered. Further to this, psycholinguistic models of verbal memory have been established to explain the multi-dimensional aspects of speech and language processing (Allen & Hulme, 2006). It has been well established that aspects of language and speech production influence how well words will be recalled and provide important understanding of the underlying mechanisms that are needed to process and retrieve words for immediate verbal serial recall.
Regardless of aspects of the stimulus, the pattern of results during verbal serial recall tasks tend to produce a typical pattern of recall that is characterised by relatively strong primacy effects with a steady decrease in recall during the middle serial positions which tend to flatten out, and a slight increase in recall for the recency items (Tan & Ward, 2008). Figure 8.1 displays a typical pattern of serial verbal recall (when items are recalled aloud), examples of the pattern of immediate verbal serial recall can also be observed within the literature (e.g. Allen & Hulme, 2006; Davis, Rane, & Hiscock, 2013; Hurlstone, Hitch, & Baddeley, 2014; Logie, Della Sala, Wynn, & Baddeley, 2000; Saito, Logie, Morita, & Law, 2008; Tan & Ward, 2008; Tindle & Longstaff, 2016a, 2016b).

This pattern of serial recall is consistently found in experiments that have implemented a serial verbal recall methodology. A majority of the research has focussed on how the stimuli and the processing demands associated with speech and language production influence performance. To date, the literature has identified that in immediate recall the recency effect benefits from the short-term activation of auditorily presented words (Pattamadilok, Lafontaine, Morais, & Kolinsky, 2010), which is in part due to the modality of the presentation (e.g. speech; Nairne, 1988). The primacy effect, has been attributed to the long-term activation of that item which allows it to be established within long term memory, as the following items are not able to be consolidated for extended periods, recall tends to be worse and flatter during the middle positions (Pattamadilok et al., 2010).
Figure 8.1. An example of a typical pattern for immediate verbal serial recall. Better recall is observed for the first item and the final item, with recall typically poorer and flatter during the middle serial positions.

Recent studies (Barrouillet & Camos, 2007; Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Barrouillet, Bernardin, & Camos, 2004) have identified a TBRS model which suggests that at any given point in time, only one task can be occurring. For example, within WM, processing/encoding and maintenance occur at separate times and attention is rapidly and constantly switched between the two (Barrouillet & Camos, 2007). The relevance of this model to the results presented in the previous chapters is the proposal that time is important for determining how well information will be remembered. This should be considered when understanding the underlying mechanisms for immediate verbal serial recall.
That is, the proportion of time an item is activated within memory is important for determining performance. To do this we must consider some of the core assumptions associated with serial recall, for example, decay, activation which is for processing/encoding (focus of attention; Cowan, 2005), and rehearsal which is for maintenance.

This chapter will propose a conceptualisation of a series of assumptions and approximations that can be implemented to predict the typical pattern of an immediate verbal serial recall tasks. The following calculations are based on the assumption that time is confined to the maximum number of serial positions \( (\text{SP}_{\text{max}}) \) in a particular task. When I refer to time I am using this as the unit of time. For example, if there are six serial positions that particular task has a maximum of 6 units \( (\text{SP}_{\text{max}}= 6) \) of time. Furthermore, I am assuming that recall begins immediately following the last unit of time, without delay. This allows us to confine the calculations to specifically identify the proportion of time items are not decaying, are rehearsed, and are activated, during the time of presentation before recall begins.

This chapter makes the assumption that that the strength of the memory trace at output is a function the rate of decay (or the proportion of time an item is not subjected to decay), rehearsal (the proportion of time that item has had the opportunity to be rehearsed) and activation (initial strength; the proportion of time an item is initially activated for) and a constant. In the context of the time-base-resource sharing model, attention is constantly switched between the processing and maintenance of items. The more items that are processed, results in an increasing number of items that need to be maintained. This suggests that attention would be captured by maintenance for longer periods as the number of items increase, thus reducing the ability for attention to switch back to processing following items and maintaining previous items. The model is therefore built on assumptions about the proportion of time an item is activated in the focus of attention, the proportion of time it can be rehearsed, and the proportion of time it is not subjected to decay before immediate recall begins. Parameters and constants are also included to account for specific experimental
factors (e.g. lexical effects, attention/cognitive load, secondary tasks) and can be calculated based on the results of previously conducted experiments. Note that for simplicity, we assume that all words are output simultaneously and immediately after the last word is presented. Therefore, this does not account for the time from the end of the list to the time the word was actually output. This could be included in the model but it unnecessarily complicates the model at this stage of development and given that not all words are output, an exact timing would be difficult to include for each serial position.

*Time without decay*

During a WM task, items are subjected to time related decay, therefore the longer the time since they were first activated in WM, the greater the risk of decay. When trying to process and maintain multiple items, the risk of decay increases due to the need to encode and maintain the newer items as well as the older items. In this example, there are two aspects to decay; time, and how many items are processed. The TBRS model suggests that resources are rapidly switched between processing and maintenance, therefore, as the item lists increases the number of items that are maintained increases.

Consistent with the TBRS I suggest that memory trace decays over item. Therefore, the strength of the memory at immediate output at the end of the list is a function of the amount of time since the item was initially heard. It is proportional to the time it was heard to the time it was output. We assume that it decays such that the memory strength at output is the inverse of the time between hearing the word and when it is output. If a word is immediately output, there is no time for decay, so memory strength would be 1/1 (i.e. there is 1 unit of time before it is output) = 1 (or 100%). For the second last word, memory strength is 1/2 (i.e. there are 2 units of time before output), for the third last word, memory strength at output is 1/3 and so on. To account for different rates of decay due to other factors such as
lexical effects, load effects etc., we can include the parameter $a$, resulting in memory strength at output due to decay being:

$$\text{decay} = \frac{1}{A^*}(\text{SP}_{\text{max}}+1-x)$$

where $A$ is a parameter to be determined, $\text{SP}_{\text{max}}$ is the list length and $x$ is the serial position in which the word was heard. This confines the memory strength after decay to a value between 0 (complete decay) and 1 (no decay). The proportion of time each serial position is not subjected to decay (when a parameter is set to 1) is displayed in Figure 8.2. The pattern in Figure 8.2 shows how items presented closer to the beginning are subjected to more time related decay, the closer they are presented before immediate recall.

Figure 8.2  The pattern for the proportion of time each item is not subjected to decay.
Rehearsal

The second assumption is that memory trace increases in strength relative to how much time it has been rehearsed. We assume that rehearsal begins at the serial position after it was initially encoded and the amount of rehearsal is a function of the number of other words that are also being rehearsed or encoded. For the word encoded at SP1, it is first rehearsed at SP2. However, word 2 is being encoded and processing must switch between encoding and rehearsal. Therefore, at SP2, word 1 is rehearsed for 1/2 of the time available. The first word is also rehearsed at SP3, but only for 1/3 of the time available at that SP and so on. Given this, the total time a word has been rehearsed is the sum of the amount of time it has been rehearsed at each serial position. For the first word this is 1/2 + 1/3 + 1/4 + 1/5 + 1/6. For the second word this is 1/3 + 1/4 + 1/5 + 1/6 and so on for each word. Since the total possible amount of rehearsal is SP_{max} - 1, to constrain this to a number between 0 and 1 (i.e. no rehearsal to 100% rehearsal) we divide SP_{max} by the above sums. Again, we can include a parameter b to account for lexical, load and other effects. Figure 8.2 shows the total relative proportion of time each item is rehearsed for when the parameters are set to 1.
Figure 8.3  The pattern for the relative proportion of time each item is able be rehearsed.

Activation/Initial memory strength

The third assumption of the model is that the initial memory strength depends on the amount of time processing can be allocated to it at encoding. The longer an item can remain in the focus of attention at encoding, the better it will be remembered. The greater the proportion of time an item remains activated, will allow greater opportunity for it to be the focus of attention. Given that attention/processing resources need to be split between encoding and rehearsal, then for the word at SP1, all of the attention can be devoted to encoding. For the word at SP2, 1/2 of the time is devoted to processing and 1/2 of the time is devoted to rehearsing the word from serial position 1. For word at SP3, only 1/3 of the time can be devoted to encoding as there are 2 words to be rehearsed, and so on. To this we can
include a parameter $c$ to account for lexical, load and other effects. Figure 8.2 displays the initial memory strength for the encoding of an item at each serial position when the parameters are set to 1.

![Graph showing initial memory strength vs serial position](image)

**Figure 8.4** The pattern for the initial memory strength as a proportion of time each item is activated in WM before immediate recall.

**Memory strength**

The above calculations have identified three core assumptions, 1. Decay, 2. Rehearsal, and 3. Activation. As each of these measures are calculated as a proportion of time and all of them impact on later recall, we are able to average across each measure to calculate a mean measure of item strength as a proportion of time. This confines the calculated memory strength at recall for each serial position to a number between 0 and 1 if the parameters are set
to 1. The parameters values are calculated when the model is fit to the specific data. At this stage, we will also add a further constant D to account for broad based lexical, load and other effects, but in order to limit the starting memory strength to between 0 and 1, this will be initially set to 0. As a further consideration, when fitting the model to the data, the memory strength will be constrained to be between 0 and 1. Figure 8.4 displays the memory strength of each item, as observed memory strength appears to resemble a common verbal serial recall pattern.

\[
MS = \frac{(DecayA + RehearsalB + ActivationC)}{3} + D
\]

_Fitting the model to serial position curve data: From previous chapters and examples from other research_

In order to test the reliability of the proposed model, the predicted pattern of memory strength was input into excel along with the verbal serial recall results from Chapter 3, 4, 6, and 7, as well as results from previously published results (e.g., Allen & Hulme, 2006; Davis et al., 2013; Logie et al., 2000; Pattamadilok et al., 2010; Saito et al., 2008; Spurgeon, Ward, & Matthews, 2014). Parameters were introduced for the values representing decay, rehearsal, and activation, while including a constant.

The solver solution in excel was used to obtain parameters for Decay (A), Rehearsal (B), and Activation (C), and a constant (D) using the sum of squares (the squared difference) between the obtained values from previous studies and the predicted values. Using the sum of squares, the parameters were calculated using Solver to minimise the sums of squares and new predicted values were obtained for each serial position. As noted above, the parameters A, B, and C were initially set to 1, the constant initially set to 0 and the memory strength at
each serial position was constrained to a value between 0 and 1 to be consistent with the proportion recall data.

**Results**

Firstly, the predicted values were calculated and the parameters were adjusted for rehearsal, decay, activation, and the constant based on the actual values obtained in the listening conditions from the experiments in Chapters 3, 4, 6, and 7. Table 8.1 identifies the actual recall score, the predicted recall value, and the parameter for A, B, C, and D.

To calculate if the predicted values were correlated with the actual values, Bivariate Pearson correlations were calculated, the results from Chapters 3, 4, 6, and 7. The results are displayed in Table 8.1, the results indicate that for these experiments the predicted memory strength calculated from the proportion of time at each serial position significantly predicts the pattern of serial verbal recall, the adjusted parameters for A, B, C, and D are also reported. Figure 8.5 displays the pattern of results for the obtained and predicted values for the experiments in chapters 3, 4, 6, and 7.

Table 8.1

*Pearson R Bivariate correlations between the predicted pattern and obtained pattern of verbal serial recall from the results from Chapter 3, 4, 6, and 7.*

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Experiment</th>
<th>List Length</th>
<th>Correlation</th>
<th>p</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3.1</td>
<td>6</td>
<td>.95**</td>
<td>.004</td>
<td>.55</td>
<td>2.81</td>
<td>2.47</td>
<td>.22</td>
</tr>
<tr>
<td>4</td>
<td>4.1</td>
<td>6</td>
<td>.97**</td>
<td>.001</td>
<td>1.33</td>
<td>6.03</td>
<td>2428.43</td>
<td>.05</td>
</tr>
<tr>
<td>4</td>
<td>4.2</td>
<td>6</td>
<td>.98**</td>
<td>&lt;.001</td>
<td>1.35</td>
<td>4.79</td>
<td>1511.43</td>
<td>.15</td>
</tr>
<tr>
<td>6</td>
<td>6.1</td>
<td>6</td>
<td>.96**</td>
<td>.003</td>
<td>.68</td>
<td>5.58</td>
<td>3657.60</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>7.1</td>
<td>6</td>
<td>.97**</td>
<td>.001</td>
<td>1.31</td>
<td>5.14</td>
<td>815.87</td>
<td>.15</td>
</tr>
</tbody>
</table>

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Thus far, my results indicate that the pattern of memory strength obtained from the proportion of time allocated to rehearsal activation and interference is significantly correlated with the pattern of verbal serial recall results within this thesis. From these results, I can conclude that the model based on assumptions related to rehearsal, initial memory strength and decay result in fits to the data showing a strong relationship between the predicted values and the obtained values in the thesis.

To further investigate the pattern of memory strength for different list lengths we obtained data from multiple verbal serial recall studies (see Table 4). The values for each serial position in all the experiments was extracted from figures within each of the manuscripts using Plot digitizer (Huwaldt, 2013). The varying list lengths were then correlated with the predicted memory strength only using parameters for A, B, C, and D for lists of 6 and 7 items. The results of the bivariate Pearson correlations are presented in Table 8.3. The results suggest that the predicted model is correlated highly with the predicted pattern of results obtained in previous studies that have used lists of 6 and 7 words.

**Figure 8.5** The pattern of results for the obtained results and predicted results for experiments 3.2, 4.1, 4.2, 6.1, and 7.1
Table 8.3

The Bivariate Pearson correlations between the predicted values and the obtained values from previous literature.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Figure</th>
<th>Items</th>
<th>Correlation</th>
<th>$p$</th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logie et al.</td>
<td>2000</td>
<td>1</td>
<td>6</td>
<td>.998**</td>
<td>&lt;.001</td>
<td>1.65</td>
<td>3.4</td>
<td>3.04</td>
<td>.23</td>
</tr>
<tr>
<td>Saito et al.</td>
<td>2007</td>
<td>2a</td>
<td>6</td>
<td>.950**</td>
<td>.004</td>
<td>5.9</td>
<td>.7</td>
<td>2.98</td>
<td>.78</td>
</tr>
<tr>
<td>Saito et al.</td>
<td>2007</td>
<td>3a</td>
<td>6</td>
<td>.927**</td>
<td>.008</td>
<td>14.1</td>
<td>3.08</td>
<td>959.99</td>
<td>.56</td>
</tr>
<tr>
<td>Saito et al.</td>
<td>2007</td>
<td>4a</td>
<td>6</td>
<td>.932**</td>
<td>.007</td>
<td>5.63</td>
<td>1.6</td>
<td>2.6</td>
<td>.64</td>
</tr>
<tr>
<td>Spurgeon et al.</td>
<td>2014</td>
<td>2b</td>
<td>6</td>
<td>.962**</td>
<td>.002</td>
<td>3776.89</td>
<td>5.01</td>
<td>26077.99</td>
<td>.22</td>
</tr>
<tr>
<td>Allen &amp; Hulme</td>
<td>2006</td>
<td>2</td>
<td>7</td>
<td>.924**</td>
<td>.002</td>
<td>.97</td>
<td>6.36</td>
<td>9065.76</td>
<td>.17</td>
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<tr>
<td>Allen &amp; Hulme</td>
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<td>4</td>
<td>7</td>
<td>.912**</td>
<td>.004</td>
<td>.91</td>
<td>6.21</td>
<td>201.8</td>
<td>.15</td>
</tr>
<tr>
<td>Davis1a</td>
<td>2013</td>
<td>1a</td>
<td>7</td>
<td>.990**</td>
<td>&lt;.001</td>
<td>1.55</td>
<td>2.32</td>
<td>9.23</td>
<td>.56</td>
</tr>
<tr>
<td>Davis1b</td>
<td>2013</td>
<td>1b</td>
<td>7</td>
<td>.932**</td>
<td>.002</td>
<td>2.49</td>
<td>3.05</td>
<td>6.68</td>
<td>.35</td>
</tr>
<tr>
<td>Davis3</td>
<td>2013</td>
<td>3</td>
<td>7</td>
<td>.938**</td>
<td>.002</td>
<td>1.53</td>
<td>3.96</td>
<td>15.86</td>
<td>.43</td>
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<tr>
<td>Pattamadiolk</td>
<td>2010</td>
<td>1</td>
<td>7</td>
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<td>.002</td>
<td>1.36</td>
<td>6.23</td>
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<td>.2</td>
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<tr>
<td>Spurgeon7_2b</td>
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</tr>
<tr>
<td>Spurgeon7_6b</td>
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<td>2b</td>
<td>7</td>
<td>.966**</td>
<td>&lt;.001</td>
<td>68731.55</td>
<td>7.8</td>
<td>3489.26</td>
<td>.04</td>
</tr>
</tbody>
</table>

Discussion

The results indicate that the observed pattern across the serial positions can significantly predicted for the results with lists of 6 or 7 words. It appears that the pattern of memory strength reliably predicts the pattern of recall across a verbal serial recall task for the results within my thesis and across multiple experiments, when parameters are adjusted for rehearsal, decay, activation, with a constant. It is important to note that the results from the experiments obtained from the literature included lists that tested similarity effects (Logie et al., 2000; Saito et al., 2008), the role of concreteness and word frequency (Allen & Hulme, 2006), articulatory suppression (Spurgeon et al., 2014), and active interference (Davis et al., 2013). It appears that despite these different manipulations across multiple experiments, by adjusting the parameters (through model fitting) we can obtain significant correlations between predicted values and actual values across multiple verbal serial recall experiments.

The aim of this chapter was to demonstrate that the relative time an item has the opportunity to be processed and maintained can significantly predict the pattern observed in an immediate
verbal serial recall task. To this end, the chapter has shown that time (e.g. related to how long the memory trace is decaying, how much time it is being rehearsed) might be an important factor in predicting verbal serial recall, and lends support for the TBRS model.

These findings provide evidence that the pattern of serial recall is time dependent, the typical pattern of verbal serial recall can be reliably replicated for experiments that have used immediate verbal serial recall with lists of 6 words. For the primacy items, resources are at their maximum availability at serial position 1, this ensures efficient encoding and maintenance of that item for a relatively longer period than the following items (serial positions 2 – 5). The recency items experience a slight increase in recall compared to the middle positions. This is likely due to short-term memory’s ability to maintain recent items relatively well for immediate recall (Pattamadilok, Lafontaine, Morais, & Kolinsky, 2010; Saito, Logie, Morita, & Law, 2008; Spurgeon, Ward, & Matthews, 2014), but also due to the item being activated in memory for immediate recall, before decay occurs.

In relation to the results in my previous chapters, this model fits well within the scope of the TBRS model. It suggests that the relative time an item can be processed and maintained in WM can significantly predict the pattern of verbal serial recall. Words that can be processed and maintained for relatively longer periods will be remembered better. In regard to the finding that handwriting reduces verbal serial recall, I can suggest that when a secondary task is added to verbal serial recall, that attention is captured by the secondary handwriting task that limits WM from switching resources back to processing and maintenance. This explains why there are typically differences confined to the middle serial positions. Based on the model proposed here, the middle serial position have relatively poorer performance because they are activated for relatively shorter periods but also subject to reductions in activation, maintenance, and processing. When a secondary handwriting task is implemented this may further limit the proportion of time these items can be activated, maintained, processed, and remembered.
This chapter is only exploratory and is an initial attempt at quantifying how the allocation of time to various processes can be used as a predictor of verbal serial recall. This chapter has provided evidence that patterns of serial recall can be attributed to processes related to the proportion of time words at each serial position decay rehearsed, maintained, and encoded. Further research is needed to explore this concept and validate the extent to which time is involved in verbal serial recall, however, this is beyond the scope of my thesis.
Chapter 9 – General Discussion

My purpose for this thesis was to assess if handwriting reduces WM performance when performed simultaneously with a verbal serial recall task and to identify what component of handwriting (phonological or motor) is contributing to the reduction in performance. Throughout this thesis, I have consistently demonstrated that handwriting, pseudo-handwriting, and other motor-drawing tasks reduce performance on a concurrent verbal WM task performance. Furthermore, I have successfully demonstrated that the reduction in performance while simultaneously writing down word lists while listening can predominantly be attributed to the motor-component of the handwriting process. In the closing experiments (Chapter 6 and 7) I aimed to show if attention capture was the cognitive mechanism contributing to the reduction in WM performance. I argue that the results present strong evidence for a TBRS model.

The results I found in the experiments presented in this thesis have provided further insight into how writing interferes with working memory. The results that I have presented were not obvious prior to these studies and have provided a unique insight into the underlying mechanisms of how handwriting is reducing working memory performance. Based on previous research it was expected or assumed that the verbal component of handwriting was largely responsible for reducing working memory performance. This is justified based on Baddeley’s suggestion of dual modality interference (e.g., working memory performance is reduced when two verbal task completed simultaneously), the generation effect, and the doodling effect. The results I have presented in this identify that the reduction in verbal serial recall performance during handwriting is largely due to the motor component of handwriting, with little additional reduction that can be attributed to the verbal aspect. The experiments I conducted in this thesis, to my knowledge, are some of the first to explore the impact of handwriting during the encoding phase of a simultaneous verbal serial recall task.
The first experiment (Chapter 3) built a foundation for the thesis; identifying that writing down lists of words while listening to them reduced recall performance significantly more than just listening to words lists or reading word lists. To investigate this, participants completed three serial recall tasks. These were reading lists of words before recalling them, listening to lists of words before recalling them, and listening to lists of words and writing them as they heard them, then recalling them. The hypothesis that fewer words would be recalled when writing was supported. Furthermore, I identified that differences in recall occurred between all three conditions at different serial positions. This suggested that handwriting overloads WM more than reading and listening, specifically during the early to mid-serial positions. This first study established that a concurrent handwriting task reduces WM performance across a serial position curve. From this, I aimed to investigate what component of handwriting (e.g. motor or phonological) led to the reduction in verbal serial recall performance. This was investigated by manipulating the different components of handwriting by looking at how pseudo-handwriting interfered with verbal serial recall performance.

The experiments in Chapter 4 attempted to dissect the handwriting task by identifying how each aspect of handwriting was contributing to the reduction in WM performance. The experiments were designed to confirm if WM performance deteriorates during a concurrent handwriting task, and if so, to isolate what component of handwriting (motor or verbal) contributes to that interference. To do this, verbal recall was investigated under three different conditions, a listening task, a handwriting task, and a pseudo-handwriting task. Recall was compared between conditions and at each serial position. The results of the study supported previous findings on the complex nature of handwriting indicating WM performance is affected when asked to write down words for children (Bourdin & Fayol, 1994) and adults (Bourdin & Fayol, 2002). The experiments suggested that when attention is captured to produce complex handwriting movements it prevents resources from switching back to
process, maintain, and retrieve items in WM (Barrouillet et al., 2004; Barrouillet & Camos, 2007). More importantly, I successfully dissected the verbal and motor components of the handwriting processes. I uniquely identified that the movements needed to produce legible and fluent handwriting are predominantly responsible for the reduction of WM performance.

The first three experiments established that handwriting and pseudo-handwriting reduce verbal serial recall performance. I then argued that this difference is largely due to handwriting capturing attention for relatively long periods of time, which prevented resources from switching back to processing and maintaining items in WM. At this point, I had not investigated if handwriting performance (as measured by movement kinematics) was also affected when performed with a recall task. The experiments in Chapter 5, were designed to investigate if there was a relationship between kinematic measures of handwriting and WM performance. The chapter also addressed the extent to which resources are shared between WM and handwriting. This was done by comparing handwriting kinematic performance when asked to simply write down lists of words without having to recall them and writing words down when the goal was to immediately recall them.

The experiments in Chapter 5 did not identify any reliable or consistent relationship between handwriting kinematics and verbal serial recall, as there is little variability in handwriting fluency across the serial positions. In addition to this, the evidence identified that handwriting performance does not deteriorate when performing a concurrent WM task, despite the strong deterioration in recall found in the handwriting and pseudo-handwriting condition in experiment 4.1 and 4.2. The results suggest that there needs to be a level of consistency of movement in order to complete the handwriting task. The way participants wrote (i.e. the kinematics) did not change significantly when they were required to recall the words. Participants did not substantially divert attention away from the handwriting task or reduce the quality of their handwriting to compensate for the demands of the verbal serial recall task.
From the results of Chapter 5, I can conclude that in terms of performing handwriting and WM tasks simultaneously, verbal serial recall suffers, while handwriting fluency is largely unaffected. Essentially, in order to perform a handwriting task attention is automatically captured to maintain and perform the complex motor movements. This in turn limits the time attention can be switched back to processing and maintenance, reducing the efficiency of WM. These results additionally emphasise that handwriting movements capture attention and prevent resources from switching back to WM processing and maintenance. To further investigate whether attention is the mechanism that is captured during a handwriting and WM task, a triple-task paradigm was implemented in order to see if that will overwhelm the available resources and impact on performance of all tasks.

The experiment in Chapter 6 investigated the role of attention in WM and handwriting by increasing the attentional load of a concurrent tapping task. Participants completed three WM tasks; they listened to words while concurrently producing pseudo-handwriting; listened to words while pseudo-handwriting and simultaneously producing finger taps with a single finger (single tap condition) or with two fingers (double tap condition), with their non-dominant hand. The double tap condition resulted in a decrease in performance for recall, handwriting fluency, and tapping speed compared to the drawing and single tap conditions. However, no differences occurred between the drawing and single tap conditions. It is concluded that by increasing the complexity of a concurrent tapping task we can achieve a decrease in performance across multiple cognitive processes. The results provided support for a central pool of shared resources that is utilised by non-WM tasks and those reliant on WM. The observed decrease in cognitive performance was dependent on task complexity rather than just performing an additional task. In the context of Barrouillet and Camos’ (2007) TBRS model, I can support their suggestion that attention capture may explain differences in performance between competing tasks rather than the existence of a central bottleneck.
Chapters 3 to 6 provided solid evidence that handwriting captures attention and prevents resources from switching back to processing and maintenance. It is argued that this is largely due to the motor component of handwriting. To provide further convergent evidence that fine motor movements capture attention a final experiment was conducted (Chapter 7). The study investigated whether performance on the verbal serial recall task was dependent on how long attention is captured and held by a secondary task, and that it is the movement aspects of the currently studied secondary tasks that are capturing attention. To do this, participants completed three verbal serial recall tasks where they recalled words after listening to word lists (of six words) or after listening to word lists while producing discrete (star) or continuous (circle) movements. The results demonstrated that fine motor movements reduced WM performance; however, it was not merely performing a movement but the type of the movement that determined how resources were diverted. In the context of the TBRS model, continuous movements were capturing attention for longer periods relative to discrete movements, reducing verbal serial recall.

9.2 Handwriting and working memory

The results have consistently demonstrated a reduction in WM performance when a handwriting, pseudo-handwriting, or drawing task was completed simultaneously. The reduction in performance as well as the pattern across the serial position has been consistent showing a strong primacy and moderate recency effect across all conditions for verbal serial recall. There was also a consistent reduction in performance during the middle serial positions typically at serial positions 3-5.

The most robust and consequential result of my thesis was the identification of which mechanism of handwriting was contributing to the interference in WM processes. Kellogg’s theory of WM in writing identified that writing utilizes different WM processes and engages with all facets of WM, including the phonological loop, visual and spatial WM, and the
central executive. The experiments I conducted looked at what aspect of the handwriting process contributed to the reduction in WM. What I found was surprising; the results indicated that the motor component of handwriting predominantly contributed to the reduction in WM performances. I suspected that at least some of the variance in the disruption of WM was due to the verbal component handwriting; however, what I found was that reduction in performance can be largely attributed to the motor component. Based on the TBRS model, it was expected that the addition of the verbal component of handwriting should have added an extra process to the task which would capture attention for a significantly longer period, compared to the pseudo-handwriting condition (that did not have a verbal component). What I found was that there was no difference between handwriting words and pseudo-handwriting however both differed significantly from just listening. This finding indicated that the verbal component of handwriting did not contribute to a reduction of WM performance.

This finding is novel and contrary to what previous literature would predict and is a key finding of my thesis. This identifies that the complexity and difficulty to produce fine motor movements is greater than what is expected and the attention needed to produce those movements significantly reduces the performance on a concurrent WM task. Further to this, I have identified something unique with how recall is differing when introducing a handwriting or pseudo-handwriting task. When looking at the differences at serial positions between conditions we can begin to see how the divergence of attention is allocated towards the different tasks and identify at what point WM processes reach their limit and become overloaded.

What I have found is that recall begins to decline around the early to middle serial positions; this is even evident in the listening condition with no secondary task. What was interesting is that it was at these serial positions WM performance began to diverge when a secondary handwriting, pseudo-handwriting, or drawing task was implemented. What this
suggests is that WM is limited to a certain number of words, in this case 3-5 items in a serial recall task, this was supported by the findings in all the experiments, where on average participants recalled approximately 3 items per list. It implies that at these serial positions WM resources are at their lowest and processing and later retrieval of these items is at its limits. This effect is further exacerbated when a secondary task is introduced. What we begin to see is a divergence of WM performance at the serial positions where performance is already at its worse. When adding a secondary handwriting task, resources are captured resulting in a reduction in WM performance that is confined to the middle serial positions. Indicating that the limits of WM performance and processing of items is centered around 3-5 items. Based on the experiment in chapter 6, I suspect that the divergence in recall performance between conditions is due to attention being captured by the secondary tasks, preventing resources from switching back to processing and maintenance.

Kellogg (1996) identified that the different components of writing utilize both the visual and spatial domain as well as the phonological domain, while the central executive devotes resources to both processes and maintains the efficiency of the written output. The results pulled apart this model to some extent to identify how the different components of handwriting might be contributing to a reduction in WM performance. What I have found is that the reduction in verbal WM performance can be attributed to the visual and spatial components of writing. Based on the findings from chapter 4, I can conclude that the movements produced during handwriting were sufficient enough to reduce verbal WM performance. I attributed this to the complex and demanding nature of the fine motor movements of handwriting that capture attentional resources preventing them to be focused on WM processes. The concept of attention capture from fine motor movements was confirmed in chapter 7 when the pseudo-handwriting and tapping paradigm was investigated, showing a decrease in WM performance when attention demand was systematically increased.
This finding has further implications for the models of WM. The results lend additional support for the concept of a general attention capacity of WM rather than domain specific limitations. In particular, the findings lend support for the TBRS model. The pattern of results and the identification of the capturing of attention is in line with the assumption of this model. One of the key assumptions of the model is that a secondary unrelated task that captures attention would result in a reduction in the ability to divert resources back to the processing and maintenance of items within the focus of attention. In relation to the handwriting task, within the context of Barrouillet and Camos’s (2007) model, the dual task nature of handwriting is attention demanding (Kellogg, 1996) and captures attentional resources to processing written output at the cost of maintaining and processing items within WM. The effect of handwriting is noticeable during the middle serial positions when attention is captured by multiple cognitive tasks and an increasing number of items to maintain in WM. At this point the allocation of attention for processing and maintenance is at its limits and the demand of the handwriting task captures attention for significant periods preventing the efficient maintenance of multiple items in WM.

It is clear that the reduction in performance between the listening conditions and the pseudo-handwriting and handwriting conditions can be attributed to the attention demanding nature of the motor component of handwriting. The attention that is needed to produce written material demands significant amounts of attention that reduces the ability for attention to be switched back to maintaining and processing items held in WM.

9.3 Limitations and future research

In general, my findings have uniquely identified that handwriting movements are largely responsible for the reduction in verbal serial recall performance. However, I did not further investigate why the verbal component of handwriting did not contribute to a reduction in performance. It seems counterintuitive that a task with an additional component would not result in attention being captured for a relatively longer period. I suspect that this may be due
to WM and handwriting utilizing the same verbal store to process the word for WM storage and for the preparation of handwriting. If this outstanding question is answered in future research, the robustness of my findings would be further enhanced. While I can determine that handwriting movements capture attention I can only speculate on why the verbal component of handwriting does not have an additional effect, or why it is possible that it should not have an effect. It would be beneficial for future research to investigate the interaction between verbal WM and the verbal aspect of handwriting.

A criticism of the studies may be that it is difficult to attribute the absence of differences between the handwriting and pseudo-handwriting task and their effect on recall to only the motor component. It could be that the reduction in recall for the handwriting and pseudo-handwriting conditions is because the two tasks utilize separate cognitive mechanisms, which are both demanding enough to capture attention. However, I argue that the main difference between the handwriting task and the pseudo-handwriting task is that there is an additional verbal component to the handwriting task that is not present in the ‘el’ combinations, and even more so in the inverted ‘el’ combinations. Additionally, the use of e’s and l’s has been shown to resemble handwriting movements (as outlined in Chapter 1 and 2), and within the literature has been a reliable indicator of handwriting movements. When designing these conditions, it was the aim to have a standard handwriting-like movement task that was as similar to writing as possible without the addition of a verbal component. I believe that this methodology is a good starting point to investigating this phenomenon. However, future research should aim to develop tasks that further isolate the verbal and motor aspects of handwriting that allows a greater manipulation of the components to identify their unique contribution to the reduction of WM performance while writing.

Another consideration of my thesis was that there was no consistent or robust relationship between the handwriting kinematics and WM performance. Previous literature identified that a relationship existed between writing speed (e.g., speed of sentence
production) and WM performance (e.g., reading span) when the two tasks were performed independently of one another (Peverly, 2006). Based on this, I expected that a similar pattern of results would occur, specifically for handwriting speed and verbal serial recall. However, no reliable relationship was found. This finding may be due to the different nature of the tasks compared to previous literature (i.e., concurrent tasks vs separate tasks). It is also possible that because the sample consisted mainly of undergraduate university students that their handwriting is relatively fluent which would result in a lack of variability in handwriting fluency. It would be beneficial for future research to screen participants handwriting to determine relatively fluent and dysfluent writers before investigating the relationship between handwriting fluency (as measured by kinematics) and verbal serial recall performance, when performed simultaneously. This would allow a sample that has variation in kinematic measure of handwriting fluency, giving a more robust and reliable sample.

9.4 Conclusion

Within this thesis, I have successfully identified that handwriting interferes with WM processing during a verbal serial recall task. When performing a handwriting task, the ability to immediately recall information is impaired relative to just listening. Further to this, I have shown that the interference can be attributed to the motor component of the handwriting process. I argue that this interference is due to limitation in attentional resources, and that tasks that require attention cause resources to divert and reduce the availability process information in WM. When resources become limited, performance on WM tasks suffer. The results have broader implications for theories of WM and provide further evidence for a TBRS model rather than domain specific limitations. Further research is needed to validate the role of attention in WM and writing as well as the relationship between writing fluency and WM performance when performing the tasks concurrently. My thesis has provided evidence to show that writing down information while listening is not the most advantageous method to utilize when required to immediately recall information. It has also identified that
movements produced during writing are complex, demanding and contribute significantly to
the reduction in the ability to retrieve information.

As stated by Plato (c. 429-347 B.C.E, as cited in Hackforth, 1952) “If men learn this, it
will implant forgetfulness in their souls; they will cease to exercise memory because they rely
on that which is written, calling things to remembrance no longer from within themselves, but
by means of external marks. What you have discovered is a recipe not for memory, but for
reminder...”. It appears Plato was not too far from the truth. I have demonstrated that
handwriting does reduce the ability to immediately recall information. This reduction in
performance is largely due to attention being captured by the motor aspects of handwriting,
which prevents resources switching back to processing and maintaining items within WM.
References


Audacity 1.2.2 [Computer software audio editor] (2004) Latest version (1.2.6 as at December 2006) freely available for all computer platforms from: http://audacity.sourceforge.net/


http://doi.org/10.1037/0278-7393.3.3.639


http://doi.org/10.1016/s0022-5371 (72)80001-x


223


http://doi.org/1.3758/BF03197724


Morey, C. C., Morey, R. D., van der Reijden, M., & Holweg, M. (2013). Asymmetric cross-domain interference between two working memory tasks: Implications for models of


http://doi.org/1.1080/20445911.2015.1135930


References


http://doi.org/1.3758/s13423-014-0773-4


Appendix A - Working Memory Methodology

Working memory span tasks

Complex span tasks are used primarily to test the capacity limits of working memory. The first example of a WM span task was the reading span task (Daneman & Carpenter, 1980). The premise of WM span tasks is the ability to serially recall items that are presented intermittently with a distractor task. In essence, span tasks consistently measure the same construct but differ in the items that are to be recalled and the nature of the distractor task. Common span tasks include Daneman & Carpenters (1980) reading span task, which required participants to read sentences and remember the last word in the sentence. The last word in the sentence was the to-be-remembered item and the reading was the distractor task. Participants were then required to recall the words in the correct order. Reading span was calculated as the maximum total amount of words recalled correctly.

The spatial span (Shah & Miyake, 1996) was developed to test the capacity of spatial working memory. In this task participants are presented with a series of capital letters consisting of their mirror images that are oriented to different degrees. Participants must decide whether the letter was the normal or mirrored image. The WM task requires participants to keep track of the sequence of orientations in each set, participants must then recall the orientation in the correct serial order. The maximum number of orientation sequences that can be remembered is used as a measure of spatial WM span.

The operation span (OSSPAN; Turner & Engle, 1989) is another widely used WM span task. This task requires participants to read a word that is to be remembered after completing a simple mathematical problem. For example, Participants might be asked a math question (10/2 x 3) and then read a word, the number of words to be remembered is increased until the participant can no longer recall the words in the correct serial position. This maximum number words are used as their WM span. Further developments to OSPAN lead to the
development of the automated version of the operation span (AOSPAN; Unsworth, Heitz, Schrock, & Engle, 2005).

The AOSPAN was developed to relieve the pressures and demand placed on both the experimenter and participants. The original span tasks are run by the experimenter, in that the experimenter moves the participant through the different stages of the task, in order to correctly identify when the participant has reached their maximum span. As pointed out by Unsworth et al (2005) this examination process is both time consuming and is subject to errors in calculating scores. The AOSPAN enables participants to complete the task without the experimenter present and is operated by the participant using a computer. This task differed slightly compared to the OSPAN by presenting letters rather than words (for an explanation of this please refer to Unsworth, Heitz, Schrock, & Engle, 2005). During the AOSPAN participants were presented a math problem which must be solved. For example, the screen displays “3 X 6 = “, the next screen displays a potential answer “18”, to which the participant must answer True or False Participants were encouraged to solve more than 85% of the math problems correctly, with feedback provided after every trial. To indicate if they had solved the math problem participant’s clicked the mouse, after this they are presented with a possible solution and must indicate if the result is true or false, then the to be remembered letter is presented. The experiment consists of 3-7 to be remembered items, each trial is presented 3 times. For example, 5 letters and 5 maths problems are presented to the participant 3 times. In total participants are presented with 75 letters and 75 math problems.

The WM span is calculated as two separate scores, the OSPAN score is calculated as the sum of all perfectly recalled sets (Unsworth, Heitz, Schrock, & Engle, 2005) while the second score calculates the total amount of letters recalled in the correct serial position (including incorrect sets).

WM span tasks are often used to determine capacity limits of WM. In particular, the AOSPAN has shown strong construct validity and reliability in measuring WM capacity.
(Unsworth, Heitz, Schrock, & Engle, 2005). The type of span task that is used is dependent on what aspect of WM you are wishing to gain a measure on, that is spatial capacity, verbal capacity, or general capacity. The AOSPAN has become a common tool for measuring WM span as it is easily operated, independent of experimenter influence, and can be conducted by the participant external to the experimenters presence. The AOSPAN was not included in the thesis as I wanted to identify how working memory performance was affected by a concurrent handwriting task. It would be difficult and quite complex to include a writing task while concurrently completing the AOSPAN (e.g., writing words, solving math problems, and remembering letter sequences).

**Verbal n-back tracking**

The n-back task was first theorised by Kirchner (1958) to test short term retention of older adults independently of memory span. The task involved constant and rapidly changing items where participants must continually update and recall information.

The n-back task requires participants to observe a series of items and identify if the item that appears was presented n trials before. The n-back can be used for both verbal and non-verbal items therefore can measure both phonological and visuo-spatial WM (VS-WM). In verbal n-back experiments participants are asked to identify if a verbal item (letter, word or number) was presented n-trials before. For example, in a 2 back trial, participants must identify if the currently presented item is the same as an item presented two trials before. Figure B.1 shows an example of a correct 2-back trial for letters.
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Figure B.1 An example of a correct verbal 2-back task.

The n-back methodology is a valid and reliable measure of WM as it requires two of the major theoretical components used to measure WM processes; manipulation and maintenance. Participants are required to continually update the target item with each presentation, while identifying if the current item was presented n-positions before. The n-back paradigm requires constant maintenance, manipulation and retrieval of information and places a high demand on WM processes. Through adjusting the independent variable, the complexity of the n-back task can be increased or decreased (the larger the n-back the more difficult the task). The n-back task becomes substantially more difficult around 3-back (Klingberg, 2010) but there have been instances where n-back training has been successful at allowing up to 5-back (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008).

Non-verbal n-back tracking

The n-back tasks involve participants to observe a series of items and identify if the item that appears was presented n trials before. The n-back can be used for both verbal and non-verbal items therefore can measure both phonological and visuo-spatial WM. In Non-
Appendices

verbal n-back experiments participants are asked to identify if an item occurred in the same position n-trials previously. For example, in a 2 back trial, participants must identify if the currently presented item is in the same position as an item presented two trials previously. Figure B.2 shows an example of a correct 2-back trial example.

Figure B.2 An example of a correct non-verbal 2-back task.

The n-back experiment can be used to examine both verbal and non-verbal WM. It is also efficient to conduct dual task experiments by combining both verbal and non-verbal stimuli, this requires the participants to hold both the phonological (verbal) and visuo-spatial information in WM and identify if the currently presented letter (number or word) was presented n-trials before or if the current item position was the same as n-trials before. This enables WM to continually maintain, manipulate and recall both phonological and visuo-spatial information concurrently, while effectively testing the reliability and validity of dual task experiments. The n-back methodology is also an effective measure of the role of the episodic buffer in WM, specifically during dual tasks as phonological and visuo-spatial information are both exchanged and manipulated within this subsystem. Figure B.3 shows an example of a dual task n-back experiment.
Figure B.3 An example of a correct dual task (verbal and non-verbal) 2-back task.

**Visual and spatial working memory**

The visuo-spatial sketchpad (visuo-spatial sketch pad) is responsible for processing both visual and spatial information. Including colour, speed, shape, movement across space and identifying where objects lie within a specific spatial domain. The visuo-spatial sketch pad has not been as extensively studied and has received little research compared to the phonological loop, however there are still studies investigating the visuo-spatial sketch pad with many different methodologies used. There are some common characteristics and methodologies employed across a majority of visuo-spatial sketch pad experiments. Some of the common experimental designs discussed will be the Corsi-block tapping test, visual pattern test, n-back, and following spatial instructions. Investigating the visuo-spatial sketch pad can be difficult as there appears to be two domains; visual and spatial. The characteristics of some experiments do not specifically measure both aspects of the visuo-spatial sketch pad, quite often to get a proper measure of the visuo-spatial sketch pad more than one experiment may need to be implemented. For example, the Corsi-block tapping test is a specific measure of spatial WM where pattern span is a reliable measure of visual WM (Baddeley, 2012).
Corsi block tapping test

The most prominent and original method of measuring visuo-spatial memory was developed by Corsi (1972). The experimental design known as the Corsi blocks was originally implemented to tests non-verbal memory in the medial temporal lobe and was discovered to be a reliable and valid measure of visuo-spatial memory. The Corsi block tapping test is quite often used to tests spatial WM as it requires serial presentation and recall (Baddeley, 2012). While the original methodology has developed from using wooden blocks to digital computerised designs the essential methodology remains the same and is still widely used in current experiments. The Corsi-blocks is often used in measure visuo-spatial WM span

The Corsi-block methodology requires participants to repeat a set of movements in the order they were made by the experimenter (or the computer program). The participant is presented with nine blocks spread across a testing board, the blocks are then tapped or highlighted by the researcher/computer program. The participants must then tap the same sequence they were presented with. If the Corsi block tapping test is adapted to measure VS-WM span the amount of sequences usually increases (starting at 1 tap) until the participant can no longer correctly recreate the sequence. An example of a computerised Corsi lock tapping test is shown in Figure B.4.

![Figure B.4](image)

Figure B.4  An example of the Corsi block tapping test adaption in a computer program, the highlighted block resembles a to-be-remembered item in a sequence.
The Corsi block tapping test is a reliable measure of spatial WM as it demands recall of items in a serial order. Evidence of the spatial component of the Corsi block tapping test is evident in dual task experiments where Corsi-span is disrupted by concurrent spatial information, disrupting the recall of items.

Visual pattern test (VPT)

The VPT is similar to the Corsi block test, however, appears to measure visual WM rather than spatial memory. In the VPT, participants are presented with shape patterns on a checkerboard-like grid. The general procedure for VPT is as follows: Participants are presented with one visual pattern at a time beginning at the simplest matrix (2x2) for 3 seconds before disappearing from view.

The VPT requires participants to replicate the visual patterns they are presented with.

The VPT generally includes two parallel versions of the test (A and B) and either can be administered. Extensive studies have validated the consistency between the two original VPT versions. In any VPT a grid ranges from a simple 2x2 matrix to the maximum 6x5 matrix. In any given matrix half the blocks in the grid are always filled. For example, in the simplest matrix (2x2) blocks are filled while in the most complex to the maximum 6x5 matrix. In any given matrix half the blocks in the grid are filled. Visual memory relies on visual components excluding interference from verbal and spatial components. The VPT is designed to be a pure measure of visual memory, distinguishing it specifically from visual WM and spatial WM. The information presented is designed to be difficult to encode information verbally to place the demand on visual WM rather than accessing and relying on verbal WM (Della Sala, Baddeley, D’Amato, & Wilson, 1999).

In the VPT, participants are presented with shape patterns on a checkerboard-like grid. When spatial memory is required, concurrent visual information is presented, suggesting it specifically measures visual rather than spatial memory. Dual task experiments indicate disruption of item processing occurs when more efficiently. The VPT is similar to the Corsi block test, however, appears to measure visual WM rather than spatial WM.
view. The participant must then recreate the matrix by filling in the appropriate blocks on a blank grid. The participants are shown three patterns for each grid presented at each level of complexity. The participants score is recorded as the amount of correctly filled blocks in the most complex pattern recalled.

Figure B.5 An example of a simple (left) and complex (right) matrix.

Visual pattern testing is a reliable and valid measure of visual WM. Current methodology still employs this procedure to measure VS-WM, more specifically it allows an independent measure of the visual component of the visuo-spatial sketch pad. In conjunction with the Corsi block tapping test a measure of both the visual and spatial components of the visuo-spatial sketch pad can be obtained.

There are many derivatives the VPT and Corsi blocks which employ similar methodology through the use of matrices and remembering pattern sequences. Barrouillet, Portrat, and Camos (2011) investigated both visual and spatial WM span through similar methodology mentioned above. However, the capacity of participants was further manipulated by increasing the amount of items to be processed, either through the amount sequential taps, or level of complexity of filled in blocks. Further to this the amount of time individuals had to process and recall information was controlled for. The capacity of participants was affected by both task complexity and processing time for both the visual and spatial domains.
Object tracking

Tracking object over a particular dimension or space is also often used to investigate VS-WM. Object tracking involves following designated objects across a visual field and following their movements. In a simple object tracking experiment participants will be asked to look at a screen, with a fixation point at the centre of the screen. Objects such as ‘x’ or ‘+’ are often used. There may be multiple number of items displayed on the screen, with one or more objects highlighted as the targets. The designated targets are the ones the participants must track. When the trials begin all the objects on the screen begin to move, the aim of the participants is to keep track of the designated targets and identify where the items are once the objects cease moving. An example of movement tracking from Allen, McGeorge, Pearson, and Milne (2006) can be seen in Figure B.6. The velocity, angle, size time and object type differ between studies, the manipulation of these variables can increase the complexity of the task and may also be used to measure VS-WM span. The complexity of the task increases with the amount of items to be tracked, for example one target item may be tracked quite well but multiple tracking significantly increases the complexity of the task and cognitive demand on the visuo-spatial sketch pad (A. Baddeley, 2012; Cowan, 2001; Della Sala et al., 1999; Deyzac, Logie, & Denis, 2006; Gathercole, 2008; R.H. Logie, 1995; Smyth & Pendleton, 1990).

Visual tracking is quite often used in conjunction with other visual and spatial experiments and is quite effective in dual task experiments. Using visual pursuit tracking may aid in determining if a particular task is visual or spatial (Baddeley, 2012). The general nature of target tracking relies heavily on visual memory, as it requires immediate visual tracking of objects within the visual field. The random movements of objects and the randomised angles ensure it is difficult to verbalise the movements, which ensures the task is specifically manipulating visual and spatial WM.
Spatial instructions

Spatial instructions are used to determine the limits of our spatial capacity and how well participants are able to follow a set of spatial instructions and recreate the description after presentation of the stimuli. There are two main types of spatial instruction outlined by Deyzac et al (2006), route perspective and survey perspective. A route perspective, presents participants with information to get from one point to another, it makes reference to specific landmarks within the spatial environment, and these are used to navigate. The route perspective is often taken from a first person view navigating through a pre-determined environment (Taylor & Tversky, 1996). The survey perspective requires navigation through an environment from a bird’s eye view, such as looking at a map (Deyzac et al., 2006; Taylor & Tversky, 1996). Both the perspectives in Deyzac et al’s study were directions in reference to objects in the environment, for example, ‘turn right’, ‘go straight until you reach…then turn left’.

Participants are presented with a set of navigation instruction consisting of multiple sentences. Once the participant has been presented with all the instructions they must navigate
through a map that has been provided by the experimenter. A survey perspective may include a map where the participants must trace a line following the instructions presented. A route-perspective may require the participant to navigate through a maze by walking through it or navigate through a room. However, the use of technology may be more beneficial as a first person perspective can be created and participants can navigate through a computer generated environment, following the navigation instructions presented by the researcher.

This method is effective in measuring participant’s ability to navigate through spatial environments. However, due to the use of sentences to navigate through an environment this method requires phonological processing of information and forgetting may occur within the verbal component and is not a pure measure of VS-WM. Spatial instructions may be considered a dual task experiment as it requires both phonological and visuo-spatial coded information. This would also place a load on the episodic buffer as information from both sub-systems must be integrated to complete the task.

Through further manipulation and progressive research on the original visuo-spatial sketch pad methodology new aspects of the WM subsystem can be investigated. Recent methodology has identified the visuo-spatial sketch pad may be involved in more complex memory and learning. Current methodology suggests, the visuo-spatial sketch pad is responsible for remembering movements, grasping and touch (remembering pressure, temperature and pain) (Baddeley, 2012; Fiehler, Burke, Engel, Bien, & Rösler, 2008; Maxwell, Masters, & Eves, 2003; Smyth & Pendleton, 1990; Tong, Wolpert, & Flanagan,, 2002) while evidence is still inconclusive, building upon the current and traditional methodology of the visuo-spatial sketch pad is revealing previously unexplored and unknown processes of visuo-spatial working memory.
Appendix B - Word List

The metrics for the words I used in the experiments were obtained. Figure A.1 displays the normal distribution of the frequency for the mean proportion of times a word was recalled. The distribution appears normal, and nearly half the words were recalled 50% of the time when they were presented across multiple experiments at different serial positions. Figure A.2 displays the frequency for the mean proportion of times a word was recalled at each serial position. As expected serial position 1 is negatively skewed, which is what would be expected with a primacy effect, the distribution looks normal for all other serial positions. However, serial position 5 seems to be positively skewed, which is consistent with this serial position having the poorest recall. This also suggest that it has something to do with the overloading of working memory rather than the type of words that are presented.

![Figure A.1](image_url)

_Figure A.1_ The frequency distribution of the overall words recalled as a proportion of correct responses.
Figure A.2 The frequency distribution of words recalled as a proportion of correct responses at each serial position.

The results presented in Table A.1 display the correlations between the mean proportion of words recalled, serial position, word concreteness, familiarity, imitability, word frequency (KF), and number of letters. There is a negative correlation between word recall and serial position, which reflects the decay of information over time, which is expected. However, recall is significantly correlated with word imagability, frequency, and number of letters, however despite the relationship being significant the effect is quite small, and is not of concern.
Table A.1
*Table presents bivariate Pearson correlations for between, recall, serial position, concreteness, familiarity, Imagability, word frequency (KF), and number of letters.*

<table>
<thead>
<tr>
<th></th>
<th>Recall</th>
<th>Serial Position</th>
<th>Concreteness</th>
<th>Familiarity</th>
<th>Imagability</th>
<th>Kucera-Francis</th>
<th>No. Letters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recall</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serial Position</td>
<td>-.48**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concreteness</td>
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<td>.03</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Familiarity</td>
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<td>.01</td>
<td>-.06</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Imagability</td>
<td>.12†</td>
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*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

The results presented in Table A.2 represent the metrics for each individual word that was used in the experiments. For each word, the mean proportion of times it was recalled across multiple experiments was calculated, for example if *Abode* was presented in 4 experiments, it was recalled on average 64% of the time across multiple experiments. Serial position (SP) is calculated as the average SP each item was presented at across multiple experiments. For example, *Abode* was presented on average at serial position 1.75, this indicates that despite list randomisation, it was presented towards the beginning of the list, meaning its relatively higher proportion of times recalled could be due to serial position.
Table A.2. The Mean Proportion of correct recall, serial position presentation, concreteness, Familiarity, Imagability, Number of Letter, and Kucera and Francis Frequency, for each word used in the experiments.

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