The relationship between working memory and cognitive control: The role of task complexity, organisational strategies and task-switching on the task-span procedure.

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Abstract

Humans are capable of remembering information in an active, easily accessible form. However, this is a limited capacity system, which temporarily maintains and stores information, and supports human thought processes by providing an interface between perception, long-term memory, and action. Using the task-span procedure developed by Logan (2004), the current thesis aimed to examine some of the most salient features of working memory. Specifically how processing and storage interact with working memory, the influence of organisational factors on working memory and the relationship between task-switching and working memory. Experiment 1 examined the role of increased processing requirements on working memory capacity and found that additional processing requirements impaired recall. Further, working memory capacity was influenced by task difficulty such that accuracy was higher in the easy condition than the hard condition. Experiment 2 examined the role of organisational processes on working memory capacity and task-switching. This was done by manipulating both the List-Length (Experiment 1) and the number of tasks to be recalled within the span. The results of Experiment 2 supported the results of Experiment 1 and suggested that there was a trade-off between processing and storage. In addition the results revealed that both strategic and perceptual processes act in unison on the storage of information. Thus, templates are formed in long term memory and tasks outside of these templates interfere with recall. The results of Experiment 2 did not provide support for the presence of task-switch costs above and beyond the additional cost of processing in the dual-task condition. Experiment 3 used a modified version of the task-span procedure in which participants were required to remember a list of task types. In the study phase, individuals were given a list of potential switches and each potential switch had a different symbol assigned to it (e.g. a parity judgement paired with a triangle, △=ODD/EVEN). This was changed to account for the influence of preparatory factors that occur within a typical task-span procedure and also to mitigate the role of the organisational processes. The results of Experiment 3 revealed that there are limitations in the task-span procedure as conceptualised by Logan (2004) and that switch costs may be best defined by the switch between processing and storage/maintenance activities rather than the switch between different task-types within a sequence. All three experiments provide support for theories that propose a general capacity within working memory that is involved in both storage and processing as well as task-switching. Collectively, the findings revealed that a number of factors determine working memory capacity. Processing influences on capacity suggest that there is a central capacity (or at least a central processing limit) for both processing and storage within working memory. In addition, there are two types of organisational processes that act on working memory; conscious chunking and perceptual processes that may act at a subconscious level. The current thesis showed that the relationship between working memory and task-switching is modulated by the nature of the working memory task. This body of work has extended knowledge of the processes implicated in working memory, the influence of additional processing requirements on capacity, and how attention modulates working memory capacity.

DECLARATION

I, Sami Yamin , declare that the Doctor of Psychology (Clinical Neuropsychology) thesis entitled “The relationship between working memory and cognitive control: The role of task complexity, organisational strategies and task-switching on the task-span procedure.” is no more than 40,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signature: Date:

DEDICATION

To my parents Dr Shahid and Mrs Shagufta Yamin, to whom I owe everything and without whom I am nothing.

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We often need to remember information in an active, easily accessible form. These tasks are believed to involve working memory. The theoretical concept of working memory assumes that there is a limited capacity system, which temporarily maintains and stores information, and supports human thought processes by providing an interface between perception, long-term memory, and action (Baddeley, 2003; Jondies, Lacey & Nee, 2005; Logan, 2004). Thus, working memory is characterised as a highly interrelated ensemble of cognitive functions (Oberauer, Sub, Wihelm, & Wittman, 2003). The importance of working memory and its applicability to everyday tasks is well established, however, the more specific processes involved are less clear. Research suggests that there are three primary working memory functions: simultaneous storage and processing, supervision, and coordination of elements into structures (Buehner, Krumm, & Pick, 2005; Oberauer et al., 2003). In an experimental setting, working memory is examined using a variety of span tasks in which participants are required to learn a list of tasks and recall or recall and use them after only a brief delay.

A fundamental property of working memory is its limited capacity (Miller, 1956). The number of items that can be recalled in order perfectly is believed to be between three and seven; this is dependent on the nature of the items and the manner in which the limit is measured (Cowan, 2001; Miller, 1956). Organisational processes exert significant effects on memory, both when remembering novel information over short intervals (i.e. working memory) and when learning material over a longer term (Bower, 1972). This process is known as chunking. Chunking involves the reorganization of material into familiar or regular structures and can sometimes improve working memory performance (Bor, Cumming, Scott, & Owen, 2004; Ericsson, Chase, & Faloon, 1980). In short-term memory tasks there are several ways to group items. These include temporal, rhythmic, and/or spatial structures which can be imposed either externally or by an individual's internalized strategies.

A key issue in the field of working memory is determining when and how additional processing influences working memory capacity. In recent studies, attention has shifted towards more complex span tasks that involve not only short-term storage but also some processing component. Some research suggests that when this additional processing requirement is imposed, there is a trade-off between processing and storage due to a single yet flexible facility of limited capacity that can accomplish both processing and temporary storage of information (Just & Carpenter, 1992; Newell, 1990). This view suggests that as processing or storage demands exceed a predetermined limit, an individual's performance on a task will deteriorate. Other theories suggest that there is fact no trade-off between processing and storage (Barnard, 1999; Engle, Kane, & Tuholski, 1999; Kane, Bleckley, Conway, & Engle, 2001; Kieras, Meyer, Mueller, & Seymour, 1999; Salthouse, 1996); this has been linked to the operation of a multiple-component working memory system thought to offer online processing and temporary storage of information by means of a number of specialized cognitive functions (Baddeley, 1986; Baddeley & Logie, 1999). Within a multiple component model, each task is believed to draw specialized resources. This perspective suggests that it is not the overall cognitive demand of the dual-task that determines performance reduction but the types of tasks combined (Cocchini, Logie, Della Sala, Macpherson & Baddeley, 2002).

More recently, research has examined the relationship between working memory and task-switching. The ability to switch flexibly between tasks allows people to adapt to changing demands in the environment however task-switching comes at a cost. Switch costs reflect the control processes that are engaged when individuals switch between two competing tasks. Working memory tasks often require the flexible allocation of attentional resources and task-switching is a way of examining the role of attention on working memory (Bunting, 2006; Bunting & Cowan, 2005; Halford, Cowan & Andrews, 2007). The task-span procedure, developed by Logan (2004; 2007), was designed to specifically examine the relationship between working memory and task-switching. In this procedure, individuals are given a list of tasks to perform and then a series of stimuli to perform them on. The task-span procedure requires working memory to store the list of task names and keep track of progress through the list. It requires task-switching because successive tasks on the list are generally different. Although only an emerging field, examining the relationship between task-switching and working memory allows researchers to investigate the influence of cognitive control of attention on working memory.

This thesis aims to integrate and test theories of working memory, by implementing established as well as modified paradigms. The influence of processing on storage and how this influences capacity will also be examined to determine whether working memory is best defined as a single, flexible capacity system or as a system of multiple interacting components. Research suggests that organisational factors such as chunking influence the amount of information that is held in working memory. Thus, the underlying processes in chunking and their relationship to working memory capacity and task-switching will be explored. Task-switching is a way of examining the role of attention on working memory and the current thesis aims to examine how these processes are linked. This thesis will review the most prevalent theories of working memory and the way in which working memory capacity is modulated by processing, organisational processes and task-switching.

1.1 Working Memory

Remembering a shopping list involves a series of steps and requires us to hold information in our mind and use it at the same time. We may group these items into various component categories, such as ingredients required for a dinner party, for the upcoming weekend, or items for a picnic. In addition, these items might involve several different perceptual subsets independent of conscious grouping or chunking i.e. fruits, vegetables, dairy, and meats. The items stored in memory need to remain activated and they may also require additional processing. For example, we might need to calculate the benefits of buying a product in a larger quantity. Thus, both storage and processing components are required to perform these tasks simultaneously. Tasks such as these are believed to involve working memory.

The theoretical concept of working memory assumes that there is a limited capacity system, which temporarily maintains and stores information, and provides an interface between perception, long-term memory, and action (Baddeley, 2003; Jondies, Lacey & Nee, 2005; Logan, 2004). Thus, working memory is characterised as a highly interrelated ensemble of cognitive functions (Oberauer et al., 2003).

Working memory plays a crucial role in high-level cognition, including reasoning (Kyllonen & Christal, 1990), reading comprehension (Daneman &

Carpenter, 1980; Just & Carpenter, 1992), mental arithmetic (Hitch, 1978), and problem solving (Engle, Tuholski, Laughlin, & Conway, 1999). Indeed, working memory has been closely linked to *g,* which reflects the component of variance that is common to all tests of cognitive ability (Colom, Rebollo, Palacios, Juan-Espinosa & Kyllonen, 2004). There is also a substantial body of evidence that proposes verbal working memory is vital to language acquisition whereby it acts to store unfamiliar sound patterns of words until more stable and long-term representations can be established (Duyck, Szmalec, Kemps & Vandierdonck, 2003). Collectively these findings underline the importance of working memory within the broader cognitive architecture.

The importance of working memory and its applicability to everyday tasks is well established, however, the more specific definition and the processes involved in working memory are less clear. Research suggests that there are three primary working memory functions: simultaneous storage and processing, supervision, and coordination of elements into structures (Buehner, et al., 2005; Oberauer, et al., 2003). At a superficial level, working memory seems functionally indistinguishable from short-term memory i.e. to temporarily store information in an activated state. Nairne (2002) suggested that the standard model of remembering over the short-term consists of storage arising from activation, a property that keeps information in an immediately accessible form. Activated information rapidly returns to an inactive state unless it becomes the focus of limited-capacity attentional processes. Some theorists argue that working memory includes short-term memory as well as the attentional processes used to keep some short-term memory content in an activated state (Cowan, 1988; 1995). Similarly, Engle et al. (1999) conceptualized working memory as a system consisting of a store in the form of long-term memory traces active above threshold, processes for achieving and maintaining that activation, and controlled attention. These theoretical accounts suggest tasks that measure short-term memory should be distinguishable from, but related to, tasks that measure working memory. That is, because short-term memory is a subset of working memory, (i.e. working memory = short-term memory + attention), performance on short-term memory tasks should be related to performance on working memory tasks (Colom, Jung, & Haier, 2007). Working memory, as a whole, can be simply defined as the collective set of this activated information in memory (Cowan, 1995). Activation is fragile and can be quickly lost through the operation of decay (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Cowan, 1995; Cowan, Wood, Nugent, & Treisman, 1997). Rehearsal allows these memory traces to remain active. When necessary, rehearsal can counteract decay, by refreshing activation (Cowan, Wood, Wood, Keller, Nugent, & Keller, 1998).

Working memory has been operationalised using a variety of techniques to examine the underlying processes involved. For example, early tasks required individuals to learn sequences of numbers (Miller, 1956; Ryan, 1968). In recent studies, attention has shifted towards more complex span tasks that involve not only short-term storage but also some processing component. Working memory span tasks, such as the counting span (Case et al., 1982; Conway, Kane, Bunting, Hambrick, Wilhelm & Engle, 2005), operation span (McCabe, 2008; Turner & Engle, 1989; Unsworth & Engle, 2005), and reading span tasks (Daneman & Carpenter, 1980) are among the most widely used measurement tools in cognitive psychology for examining working memory.

This section has briefly outlined the most basic aspects of working memory, the relationship between short-term memory and working memory, the operationalisation of working memory and the relationship between working memory and other higher-order cognitive functioning. Working memory as a concept is far more complex than the simple definitions given here and the next section will highlight how working memory is theoretically conceptualised by examining some of the most prevalent models of working memory.

1.2 A Theoretical Perspective: Models of Working Memory

Since the time of Miller's (1956) seminal work, numerous models have been devised to explain the ability to temporarily store information and use it. There is significant disparity in the way working memory is conceptualised, however, there are several features that are generally agreed upon. Working memory is a temporary storage system with capacity limitations that requires reactivation in order to avoid rapid decay of information. The fundamental processes that underlie most models of working memory are encoding, maintenance and retrieval. Where models tend to differ is the way in which these factors are applied. There are several issues which are central to the debate regarding the nature and processes underlying working memory (Shah & Miyake, 1999). These include the basic mechanisms and their representation within working memory, control and regulation of working memory, the unitary or non-unitary nature of working memory, the nature of working memory limitations, the relationship between working memory and long-term memory, and the relationship between working memory and attention. Models of working memory can be divided into two basic categories 1) models that view working memory as a complete system in itself with connections to other systems (e.g. Baddeley & Hitch, 1974) or 2) or those which conceptualise working memory as part of a larger cognitive architecture that incorporates several aspects of higher order cognition (e.g. Lovett, Reder & Lebiere, 1997).

One of the first, and perhaps the most influential working memory model was devised by Baddeley and colleagues (Baddeley, 1986; 1992; Baddeley & Hitch, 1974). They proposed a three-component model of working memory that comprised an attentional control system, termed the 'central executive', and two subsidiary slave systems, the 'phonological loop' and the 'visuospatial sketchpad'. The phonological loop is assumed to hold verbal information by using a temporary store and an articulatory rehearsal system. The sketchpad is assumed to hold visuospatial information and believed to be fractionated into separate visual, spatial and kinaesthetic components (Baddeley & Logie, 1999). The central executive is also assumed to have several components including focusing, dividing and switching attention (Baddeley, 1996; 2002; Baddeley, Emslie, Kolodny, & Duncan, 1998). More recently, Baddeley (2000; 2002) introduced a new component to his original theory of working memory: an episodic buffer which is assumed to be a limited capacity storage system capable of integrating information from a variety of sources. He argued that it is controlled by the central executive, which is able to retrieve information from the store in the form of conscious awareness, or reflect on that information and, where necessary, manipulate and modify it (Baddeley, 2000; 2002). The buffer is episodic in the sense that it holds episodes whereby information is integrated across space and potentially extended across time.

An alternative working memory model is the Embedded Process Model proposed by Cowan and colleagues (Cowan, 1999; 2001; Cowan, Elliot, Saults, Morey, Mattox, Hismjatullina, & Conway, 2005). Cowan (1999) suggested that three components contributed to working memory. Working memory information comes from hierarchically arranged processes consisting of long-term memory, the subset of long-term memory that is currently activated, and the subset of the activated component of memory that is currently in the focus of attention. He argued that attention is driven conjointly by voluntarily controlled processes and an involuntary attentional orienting system. The information in the current focus is the most readily accessible information in working memory. Information that is activated, although not to the extent of conscious awareness, can also be retrieved reliably, albeit with a slightly longer delay. Cowan (1999) argued that differing components of working memory, more specifically activation and storage, have different processing limitations. Essentially, attention is a limited capacity system such that only four chunks can be held in memory at any one time, whereas activation is time limited whereby activation of information within working memory will decay unless reactivated through rehearsal (Cowan, 1999; Cowan, Day, Saults, & Keller, 1992).

Working memory can also be defined in terms of function, namely maintaining efficient selective access to information that is needed to complete a given task. Ericsson and Delaney (1999) suggested that working memory includes all the different mechanisms that allow individuals to control and selectively access relevant information during the sequence of stable cognitive states. In particular, individuals can maintain access to information in skilled activities by encoding it in long-term memory in such a way that it can be efficiently retrieved whenever it is required to complete a task. They argued that the amount of information that can be maintained in an accessible form for a specific task is not limited by a fixed capacity. Instead, they proposed that extended skill acquisition is necessary to achieve very high levels of performance, whereby ‘experts’ acquire knowledge and skills to rapidly encode information in long term memory. Ericsson and Delaney termed this phenomenon Long-Term Working Memory (LTWM) and argued that LTWM is mediated by associative recall from long-term memory. It maintains access to memories based on temporal recency cues, an association to explicit retrieval structures, or on associations to elaborate cognitive structures, generated during learning. Furthermore, these structures may vary across individuals based on their available representations, knowledge, and preferred strategy. From this perspective, individuals need to maintain selective access to relevant procedures in addition to information that is presented, retrieved and generated, by distinguishing it from a vast amount of other knowledge and procedures stored in long-term memory.

There are several models that view working memory as part of a larger cognitive architecture (Lovett et al., 1999; Kieras et al., 1999). Within these larger architectures, models are developed to explain more specific processes such as working memory. The Adaptive Character of Thought-Rationale (ACT-R) cognitive architecture proposes that information processing depends on the goal of the system (Anderson & Matessa, 1997; Anderson, Bothell, Lebiere, & Mattesa, 1998; Lovett et al., 1999). ACT-R theory suggests that there are two ways to define working memory in theoretical terms. Firstly, to equate working memory to content that is being maintained during processing (e.g. the elements that are representing the memory items in the working memory task). This content-oriented definition includes working memory as a subset of declarative memory. Thus, working memory is not a specific system in itself, but instead declarative nodes are highly activated because they have been stimulated by the environment or are linked to current system goals (termed source activation). According to this definition, working memory consists of mechanisms acting on declarative memory, learning decay, and attentional activation (Lovett et al., 1999).

Lovett et al. (1999) suggested that working memory can also be defined by the process that enables working memory elements to be maintained. This process-oriented definition of working memory suggests nodes in the highly activated subset of declarative memory receive an important part of their activation from the process that spreads the activation. Both definitions identify the basic mechanisms of working memory as a spread of source activation. This spread mostly affects nodes that are strongly linked to the goal and the general declarative mechanisms of learning and decay.

An alternative computational model of working memory is the Executive Control/Interactive Control (EPIC) architecture that was constructed by Kerias and colleagues (Kieras, et al., 1999) for modelling cognition and action. According to the EPIC model, working memory has five partitions in total that can be divided into two categories: modal working memory stores and production-system memory stores. The modal working memory stores contain three partitions each dedicated to an individual perceptual modality (i.e. visual, verbal and tactile) and that each of these contains information about respective perceptual processors. The production-system memory stores consist of two partitions, namely the control and the tag store. The control store contains items that represent current task related goals, the steps and strategies required for goal completion, and the status of items which represent the current stages of completion of various processes. The tag stores, on the other hand, contain items that label other items in the modal (i.e. perceptual and motor) working memories. Such labelling assigns particular roles to modal working memory items referenced by the conditions and actions of production rules. Kerias et al. (1999) suggested that working memory encompasses the entire range of temporarily stored codes, knowledge representations and procedures where information is maintained, updated and applied for performing perceptual-motor and cognitive tasks. There are no limits on working memory per se; instead the limitation is caused by finite processing speed and decay of symbolic codes in partitions of perceptual working memory.

The Soar model is another broader architecture which focuses on the functional capabilities needed for a memory system to support performance in a range of cognitive tasks (Newell, 1990; Young & Lewis, 1999). The functions of working memory are distributed across multiple components of the architecture, including long-term production memory (Young & Lewis, 1999). The Soar architecture has no separate working memory mechanism as such (Young & Lewis, 1999) rather it is a production system architecture with two main memory components, a long-term production memory which stores permanent knowledge, and a dynamic memory that holds state information pertaining to the current task. The functions of working memory are distributed across both these memories. Processing occurs by cyclically choosing an operator to apply to the current state, thereby transforming it to a new state. Whenever that process is blocked, soar sees an impasse and sets up a substrate, processing of which is intended to produce information to allow processing of the original state to resume. New production rules are acquired whenever processing of a substrate generates information for the original state.

Despite the extensive and detailed theories of working memory, no single theory can explain all empirical evidence with adequate detail and without substantial modification. Many theories require the addition of a universal processor or ‘black box’ to explain complex results (i.e. Baddeley’s central executive or the Supervisory Attentional System). There are several key areas that remain contentious and require further empirical exploration. The most pertinent of these are the nature of capacity limitations and the influence of organisational structures on storage, the influence of processing on storage and the role of attention and cognitive control on working memory as examined through the relationship between task-switching and working memory.

1.3 The Nature of Working Memory Capacity Limitations and the Influence of Organisational Structures on Storage

A fundamental property of working memory is its limited capacity (Cowan, 1988; 2001; Miller, 1956). The number of items that can be recalled in order perfectly is between three and seven and depends on the nature of the items and the manner in which the limit is measured (Cowan, 2001; Miller, 1956). Early work by Miller (1956) postulated that working memory capacity is a constant number of separate mental units, or in Miller’s case “the magical number 7” whereby the number of items that could be recalled correctly for most people was seven with a variation of ± two accounting for individual differences. More recent findings using a variety of stimuli have suggested that the capacity of this system, across stimuli, is more accurately represented as three to five items rather than Miller's seven (Broadbent, 1975; Cowan, 2001; Mandler, 1975).

All theories of working memory assume that capacity is limited however they differ primarily in the assumptions they invoke to explain the limit. Some theories propose that a limited capacity for activation constrains the number of items that can be kept sufficiently active to be recalled (Anderson, Reder, & Lebiere, 1996; Daneman & Carpenter, 1980; Just & Carpenter, 1992; Logan, 1978, 1979). Other theories assume that activation decays over time and only a limited number of items can be kept active enough to be recalled (Baddeley, 1986, 1996; Baddeley & Hitch, 1974; Cowan, 1995, 1999; Hitch, Towse, & Hutton, 2001). Still other theories assume that similar items interfere with each other, and this limits the number of items that can be kept sufficiently distinct from each other to be recalled accurately (Baddeley & Logie, 1999; see also, Cowan, 1999; Hasher & Zacks, 1988; Lustig Hasher & May, 2001; May, Hasher & Kane, 1999).

Organisational processes exert significant effects on memory, both in remembering novel information over short intervals (i.e. working memory) and in learning material over a longer term (Bower, 1972). In short-term memory tasks there are several ways to group items. These include temporal, rhythmic, and/or spatial structures which can be imposed either externally or by an individual's internalized strategies. Research suggests that with adequate practice, individuals were able to increase their digit span from 7 to 79 (Ericcson et al., 1980). Ericcson and colleagues argued that the ability to store increasingly larger amounts of information in working memory was related to the sophisticated organisational strategies employed rather than a change in storage capacity. This process is known as chunking.

A chunk is a collection of concepts that have a strong association to one another and much weaker associations with other chunks (Cowan, 2001). Chunking involves the reorganization of material into familiar or regular structures and can sometimes improve working memory performance (Bor, Cumming, Scott & Owen, 2004; Ericcson et al., 1980; Gobet, 2000). Gobet, Lane, Croker, Cheng, Jones, Oliver and Pine (2001) suggested that the literature can be divided into two broad areas based on how and when chunking is assumed to occur: the first assumes a deliberate, conscious control of the chunking process (goal oriented chunking), and the second assumes a more automatic and continuous process of chunking during perception (perceptual chunking).

In serial recall tasks, Cowan (2001) proposed that people may be able to form multiword chunks rapidly when a list is presented. He suggested that there are several ways in which this can occur, such as noticing that to-be-recalled information corresponds to elements in long-term memory (e.g. recoding the digit sequence 1-9-9-5 to 1995 as designating a particular year). Early work by Wickelgren (1964; 1967) found that rehearsing in groups of three items was optimal, irrespective of List-Length. Puff (1970) found that individuals who were presented categorized lists recalled more of that list than those given a non-categorized list, even when participants did not re-order words into category clusters.

Grouping through chunking can also occur using the temporal grouping phenomena (Mclean & Gregg, 1967; Ryan, 1969). This effect arises when additional pauses are inserted in a presented list to form groups of items, for example, when a pause is placed between the 3rd and 4th, and 6th and 7th item in a nine digit list (Ng & Maybery, 2002). Early work by Ryan (1969) found that temporal grouping improved recall to a greater extent than non-temporal grouping. Further, regular patterns of temporal grouping (i.e. three clusters of four items in a list of 12 items) were significantly more accurate than irregular patterns of temporal grouping (i.e. three clusters of five, six and one item in a list of 12 items).This temporal grouping phenomena has led some researchers to suggest that grouping is time dependent by assuming that positional information is retained by associating items with contextual information. In a series of experiments, Ng and Maybery (2002) varied the time between presentation of stimuli (stimulus onset asynchrony; SOA) to examine whether grouping is time-dependent. Lists of consonants were presented visually (with vocalization) in Experiment 1, auditorily in Experiment 2, and auditorily with articulatory suppression in Experiment 3. They found that forgetting was time-independent and that within-group temporal separation of items during presentation did not influence the pattern of error across all three experiments. Instead they argued that errors in performance and intrusion errors reflected within group/chunk serial position errors.

Similar results have been found by Hitch and colleagues (Hitch, Burgess, Towse & Culpin, 1996). In a series of experiments they examined the influence of articulatory suppression on temporal grouping for visual sequences or auditory lists. They also examined the influence of the word length effect and phonological similarity on temporal grouping. Hitch and associates found that the temporal grouping effect on memory for visual sequences was removed by either articulatory suppression or reciting random digits; articulatory suppression however did not remove the temporal grouping effect for auditory lists. Hitch and colleagues concluded that the temporal grouping phenomenon is not critically dependent on rehearsal. Rather, temporal grouping has a role within the phonological loop component of working memory. At a more general level, their findings suggested that the chunking of a sequence into familiar sub-sequences may consist of similar underlying processes to temporal grouping. However, Hitch et al. suggested that chunking consists of more sophisticated processes than those involved in temporal grouping.

Previous research has found that associations between items can assist in immediate recall (Cumming, Paige & Norris, 2003; Hulme, Stuart, Brown & Morin, 2003; Stuart & Hulme, 2000). An alternative way to examine chunk length and chunking is to impose associations on to-be-remembered material. A recent study, by Cowan, Chen and Rouder (2004) assessed the hypothesis that working memory capacity should include a constant number of separate mental units or chunks. They manipulated the influence of chunking by presenting novel pairs of words (A-B, C-D, E-F, etc.) and examined the effects of these paired associations on subsequent memory tests (serial and cued recall). In order to create chunks that varied in size between conditions, Cowan et al. used a training phase to manipulate the associative strength within word pairs. In serial recall, the previously studied pairs were embedded within eight item lists, and participants were asked to recall each list immediately after it was presented. Words were presented to participants as either single-words or as pairs and varied in frequency of occurrence of the pairs (one, two or four paired presentations during a training period).

Cowan et al. (2004) found that although inducing associations between words increased the number of two-word chunks, the total chunk span (i.e. the number of singletons plus two word chunks) remained relatively constant. Further, they found that learned chunks are context specific such that they are bound in some way to correct serial positions. They concluded that the total number of chunks remained constant across association strengths and that working memory had a constant storage capacity. Thus, chunking capacity/chunk span and storage capacity may be relatively independent of one another. In other words, chunking capacity and storage capacity may rely on different underlying factors, or cognitive mechanisms and both may contribute to working memory capacity (Ottem, Liam & Karlsen, 2007).

The effect of associative strength on memory span suggests that chunk span is at least to some extent, independent of chunking capacity (Cowan et al., 2004; Gobet et al., 2001). In contrast, Ottem et al., (2007) argued that although chunk span does not rely on associative strength, chunking capacity is dependent on associative strength, or pre-existing associations between study items; chunk span cannot be determined without taking associative strength into account. An example of this was provided by Silberman, Miikulainen and Bentin (2005) who argued that strongly associated semantically unrelated words facilitate the episodic association of other words included in their semantic neighbourhoods. They found that the incidental formation of strong associations between unrelated words, such as dog and table, improved cued recall of weak associations formed incidentally between semantic neighbours, like cat and chair. Their findings demonstrated that forming episodic associations between words can implicitly mediate the association of other words from the same semantic categories and reveal a mechanism by which the semantic system contributes to the formation of new episodic associations (Silberman et al., 2005).

The question of whether immediate recall capacity is determined by either the number of chunks that can be recalled or by the length of the list of material to be recalled was examined by Chen and Cowan (2005). In their experiments, participants were required to learn new paired associations between words to create two word chunks. Each experiment had three phases: training phase, immediate recall, and free recall phase. Words during training were presented as either singletons or word pairs. Their results with free and serial recall of lists of different lengths indicated that chunk and length constraints occur under different circumstances. Performance in the free recall and serial recall conditions was similar for both the list of six learned pairs and six learned singletons as a chunk limit would suggest. In contrast, during serial recall, performance on a list of four learned pairs was very similar to performance on a list of eight learned singletons. This is consistent with a List-Length limit and not the four singletons a chunk limit would suggest. They concluded that it is likely that these two limits can operate independently or together depending on task demands.

This section has outlined a framework for understanding capacity limitations in working memory and how information can be combined to form meaningful units or chunks to improve the efficiency in the encoding of information in memory. Although most theories of working memory agree that there is only a limited amount of information that can be held at any time, the nature of this capacity limitation is unclear. The question for capacity is whether capacity limits should be viewed simply from the perspective of a limited number of units of meaningful information that can be held in mind or as a combination of storage and organisational factors. This issue is further complicated by research that suggests that additional processing requirements or the ability to effectively store information to perform a task influences working memory capacity. This ‘trade-off’ between processing and storage of information will be examined in the next section.

1.4 The Influence of Additional Processing Requirements on Working Memory Capacity: The Trade-Off Between Processing and Storage

Working memory and the temporary storage of information is often seen as an online process (Duff & Logie, 2001). As with all cognitive processing there is a maximum capacity or limit. Some researchers have suggested that cognitive resources are a single yet flexible facility of limited capacity that can accomplish both processing and temporary storage of information (Just & Carpenter, 1992; Just, Carpenter, & Keller, 1996; Newell, 1990). This view suggests that as processing or storage demands exceed a predetermined limit, an individual’s performance on a task will deteriorate. Many experiments sought evidence for the predicted trade-off, but few found it. Consequently, most modern theories of working memory do not predict strong trade-offs between processing and storage (Engle et al., 1999; Kane et al., 2001; Kieras et al., 1999).

Research examining the nature of the relationship between processing and storage has predominantly incorporated a dual-task methodology. A dual-task methodology usually involves an individual performing two tasks simultaneously and hinges on the idea that if two tasks can be performed simultaneously without producing a substantial drop in performance or a trade-off, then the two competing tasks are believed to be independent (Duff & Logie, 2001). Vecchi and Cornoldi (1999) suggested that it is possible to distinguish between simple immediate memory tasks (storage tasks) and tasks involving both retention and manipulation of information (processing tasks). Passive storage refers to retention of information that has not been modified after encoding, where encoding could be a response to external stimuli, to long-term material, or result from mental manipulation by some other part of the cognitive system. Alternatively, active processing refers to the transformations and manipulations of stored information. The outcome of an active process may be retained in the passive store or determine an external output (Vecchi & Cornoldi, 1999).

There are several different techniques used to examine the relationship between storage and processing including comparing simple and complex span tasks (Daneman & Carpenter, 1980; Duff & Logie, 2001; Vecchi & Cornoldi, 1999), operation spans (McCabe, 2008; Turner & Engle, 1989; Unsworth & Engle, 2005), memory updating procedures (Morris & Jones, 1990) and more recently the task-span procedures (used in the current series of experiments; Logan, 2004; 2006). Despite substantial research conducted it is unclear whether performance on working memory span tasks are best described as a trade-off between processing and storage within a general working memory system, or as the coordinated activity of separate processing and storage elements of a multicomponent model of working memory (Duff & Logie, 2001). This distinction between single capacity and multiple component models will be discussed at length in the next two subsections.

1.4.1 Support for a Single Capacity.

One of the most influential ideas about processing limitations is the hypothesis that the human cognitive system has a central limit that does not permit two independent cognitive processes simultaneously (Byrne & Anderson, 2001; Oberauer & Gothe, 2006). Single capacity models suggest that working memory is a limited-capacity system in which resources are shared between processing and storage. Increasing cognitive load (the amount of resources needed to carry out a task) leads to a trade-off. Thus, performance decreases when the concurrent memory load increases, and any increase in difficulty of processing results in a loss of information from short-term storage memory (Anderson, Reder, & Lebiere, 1996; Case, Kurland, & Goldberg, 1982; Conway & Engle, 1994; Daneman & Carpenter, 1980; Just & Carpenter, 1992).

Unsworth and Engle (2007) examined the trade-off between processing and storage by comparing the difference between simple and complex span tasks. In the simple span condition, participants were given a list of to-be-remembered items including letters, numbers, words, or shapes and then asked to recall the list in the correct serial order immediately after the items are presented. Complex span conditions, on the other hand, required participants to engage in some processing activity unrelated to the memory task. This activity was embedded within the presentation of the individual to-be-remembered items (Unsworth & Engle, 2007).

They found that whilst both simple and complex span tasks largely measured the same subcomponent processes i.e. rehearsal, maintenance, updating and controlled search, they differed in the extent to which these processes operated in a particular task. These findings suggest that a single capacity system is responsible for both processing and storage and that the decrease in performance in complex span tasks is due to additional requirements being placed on this processor.

Some theorists have proposed that the main difference between storage alone tasks and tasks that require both processing and storage is the benefit obtained from rehearsal during storage alone tasks (Colom, Rebollo, Abad, & Shih, 2006; Cowan, 2004). In complex tasks, the concurrent processing component of the task precludes rehearsal. Colom et al. (2006) argued that there was a general component for maintaining information in an active and reliable state and that this was determined by the efficiency of working memory. Additional processing requirements lower the reliability of temporarily stored information given that these processing requirements take away a proportion of the capacity used for temporary maintenance. Colom and associates suggested that concurrent processing requirements leave less capacity for temporary storage of information. This diminishes the reliability of the stored information, which in turn leads to a greater number of errors.

Similarly, others have argued that attention and awareness form the basis of one type of working memory storage. Bunting and Cowan (2005) used a conceptual span task, whereby semantic and colour-name cues were designed to prompt recall of four consecutive words from a twelve-word list. The first-four, middle-four, and last-four words belonged to different semantic categories and were presented in different colours. In their first experiment, the colour of the cue matched the cued items 75 percent of the time. They found that the rare mismatch (25 percent of the time) impaired recall of items on the list. Expanding on this in a second experiment, Bunting and Cowan (2005) changed the proportion of accurate cues to only 25 percent of trials. They found that when the cue-stimulus mismatch was more frequent, the influence of the mismatch was removed. They argued that these results were difficult to reconcile with a passive storage mechanism alone; they proposed that attention serves as a form of memory storage and that processing difficulty (in terms of a colour mismatch) can impede working memory recall, due to drawing attention away from a storage function.

A series of studies have demonstrated that the attentional resources allocated to the maintenance of information is modulated by both duration of task and cognitive load (Barrouillet, Bernardin, & Camos, 2004; Barrouillett, Bernardin, Portrat, Vergauwe & Camos 2007; Barrouillet & Camos, 2001; Gavens & Barrouillet, 2004). Barrouillett et al. (2007) found time is one of the main determinants of cognitive load and mental effort and the effect of concurrent activities on recall did not go beyond their duration when the processes were attention demanding. Further, spatial processing disrupted verbal maintenance suggesting that these findings were not modality specific. They proposed a sequential and time-based function of working memory in which processing and storage relied on a single and general purpose attentional resource to run executive processes devoted to constructing, maintaining, and modifying representations (Barrouillet et al., 2007).

More recently, single capacity theories have suggested that although visual and verbal information may be encoded in two different stores, there is a central capacity system that is responsible for processing. Some theorists have proposed that working memory capacity is limited by a central processing bottleneck (Oberaur & Kliegl, 2001; 2004). These theories suggest that there is a seriality constraint on processing that implies that domain specific subsystems of working memory cannot easily operate independently, even on very simple tasks (Baddeley, 1986). Oberaur & Kliegl (2004) examined this proposal by using working memory updating task (Oberaur & Kliegl, 2001; Salthouse, Babcock & Shaw, 1991) in which participants were asked to hold two items (one digit and the spatial position of a dot) in memory and to update them both numerous times according to simple rules. They found that without practice, individuals experienced significant dual-task costs when they executed two cognitive operations in working memory, even though the operations were highly different and were applied to representations from different domains. They suggested that there are constraints on processing in working memory that go beyond the limited capacity for maintenance. Although four independent chunks can typically be maintained in working memory at any time (Cowan, 2000; Halford, Wilson, & Phillips, 1998), manipulating even two of them at the same time is difficult and may be impossible without practice for most people. However when a dual-task combination of tasks was practiced, they found that two tasks could be combined with little associated cost. The same did not apply when the two tasks were practiced independently.

Theories that take into account the seriality constraint and the role of practice (Oberauer 2002; 2003) propose that a small number of chunks in working memory are maintained at any time, and a focus of attention selects one of them as the object of a cognitive operation. Since the focus of attention is the gate for inputs to cognitive operations, its limitation to a single mental object implies a constraint on cognitive operations. Only one operation can be performed at any time, that is, only the object within the focus of attention can be manipulated. The dual-task costs seen at the beginning of practice trials (Oberauer & Kliegl, 2004) support this assumption. However, after practice, most participants are able to perform these cognitive operations in parallel with little or no dual-task costs. Theories assuming a central bottleneck (Byrne & Anderson, 2001; Oberauer, 2002; Pashler, 1994a) have difficulty explaining the influence of practice. Single resource models could add a functional bottleneck for cognitive operations in working memory (a strong constraint enforcing serial processing) but one that can be overcome by learning to combine the two tasks efficiently. The constraint lies not in a rigid cognitive architecture but in a flexible configuration of the cognitive system for scheduling central operations (Oberauer & Kliegl, 2004).

Most experiments examining the relationship between storage and processing focussed on either manipulating the amount of information held in working memory or the modality of the additional processing task (i.e. when a verbal storage task is combined with a verbal processing task as compared to a visual processing task). There are relatively few studies that have manipulated the load of the processing task. Those that have, found mixed results. For example, Conway and Engle (1996) suggested that processing task complexity was only important when it was demanding enough to force an individual to shift their attention away from the storage component of the task and to engage in controlled and effortful processing. They argued that viewing time increased as a function of difficulty level but the number of words recalled did not. Thus, processing difficulty had little influence on performance whereas the attention switching was a critical determinant of span.

In contrast, Bunting (2006) found that increasing attentional demand made the primary task more difficult to perform. He examined the role of processing difficulty in working memory span. He manipulated the ease of processing in order to have minimal processing load while still preventing overt rehearsal. The memory tasks were the Operation Span (OSPAN; a storage plus processing task) and Probed Recall (PR; a storage only task), and the criterion task was Raven's Progressive Matrices (RAPM). OSPAN processing difficulty was minimized in a way that removed the demand of solving math equations while still preventing rehearsal. Task difficulty was manipulated in PR with the addition of easy and difficult distractor tasks. Bunting (2006) deduced that increasing attentional demand in the probed recall condition made the primary task more difficult to perform. This suggested that there was increasingly less room for storage as processing demands increase. Thus processing difficulty is important in dual-component working memory tasks and determines individual differences in working memory.

Similarly, several studies have shown that the capacity of visuospatial working memory is limited by complexity of information presented (Kemps, 1999; 2001). Kemps (1999) found that the determinants of complexity can be separated into a quantitative factor, which sets an upper bound on complexity, and a structural factor, which reduces complexity in visuospatial memory. Using variants of the Corsi blocks task, quantitative complexity was manipulated through the number of blocks on the board while structural complexity was induced through the positioning of the blocks.

Kemps (1999) found that visuospatial span was susceptible to both measures of complexity. Performance decreased as the number of blocks increased and recall was better when the blocks were positioned in a matrix rather than in a random fashion. She suggested that the effect of complexity was moderated by the interaction between structure and amount of information presented. These results demonstrated that both the quantity and complexity of information influenced the amount of information recalled from visuospatial working memory.

Oberauer and Gothe (2006) investigated dual-task interference between processing and storage tasks by comparing short-term storage of numerical and spatial material and the execution of numerical and spatial operations. They conducted two experiments using a working memory updating task and asked participants to memorise a set of digits and a set of spatial positions, update elements of both sets by a sequence of operations, and then recall the final values. In Experiment 1, a single element in each memory set was updated several times. In Experiment 2, individuals were required to update all elements of both memory sets in random order. They found very little interference between storage and processing when only one element had to be accessed for processing. In contrast, when all elements in working memory had to be kept ready for access, there was a greater amount of competition for a general capacity. They suggested that an activated part of long-term memory is used when items do not require processing. However, when processing is required there is a central capacity (or limited part of working memory) that provides access to its contents.

Historically, single capacity theories have considered processing and storage to be separate dimensions that load on a unitary processing resource. However, more recently a hybrid theory has been suggested that processing and storage was not merely determined by the amount of information and the addition of a processing task, but also by the complexity of both the processing and storage task and the relationship between the two. From this perspective, processing and storage are innately linked and that working memory capacity is determined by the complexity of relations that can be processed in parallel (Halford et al., 1998). The processing load imposed by interacting components of a task can be captured with the concept of relational complexity. Thus, the task becomes more complex as the number of interacting factors increases. This complexity can be measured by the dimensionality of the relation or the number of related variables.

Halford et al. (1998) suggested that the processing complexity of a task is related to the number of interacting variables that must be represented in parallel to perform the most complex process involved in the task, using the least demanding strategy available to humans for that task. Processing complexity can also vary over time within one task, hence the critical value is the complexity of the most complex step. Tasks can vary in the number of steps they require, but this does not necessarily affect processing load because a task with many steps might impose only a low demand for resources at any one time (e.g., counting peas in a box). Halford and associates (Halford et al., 1998) suggested that processing demand is the effect exerted by task complexity on an individual and reflects the required cognitive resources. Thus, the more interacting variables to be processed in parallel, the higher the demand. The resources allocated to a task vary as a function of “demand” or “load” and performance. More resources must be allocated to higher demand tasks to maintain performance (Halford et al., 1998).

More recently, Halford and colleagues (Halford et al., 2007) suggested that working memory and reasoning share the same related capacity limits. These limits are quantified in terms of the number of items that can be kept active in working memory, and the number of interrelationships between elements that can be kept active in reasoning. The latter defines the complexity of reasoning problems and the processing loads they impose. Working memory is limited to 3 and 4 chunks, and reasoning is limited to relations between four variables. One potential hypothesis is that both working memory and reasoning require items or concepts to be the focus of attention concurrently. This would enable them to be inter associated to form chunks or bound into coordinate systems, including relational representations that enable inferences to be made (Halford el al. 2007). From this perspective optimal learning of information requires the reduction of complexity of information to a level that does not exceed capacity (Elman, 1993).

Despite the acknowledged importance of processing complexity in relation to storage, few studies examined the processing limits of variables (Halford, Baker, McCredden & Bain, 2005). Assessment of processing capacity is difficult as individuals use strategies aimed at reducing processing load in order to optimise capacity (Hirst, Spelke, Reves, Caharack, & Neisser, 1980). The relational complexity theory provides a holistic approach and accounts for numerous empirical studies and importantly accounts for strategy use in the reduction of overall task complexity.

Theories that support a single capacity suggest a general processing system is responsible for both processing and storage of information in working memory. They draw on findings from research that has found that when additional processing of information in working memory is required, storage capacity is reduced. More recently, theories have proposed that there is an attentional resource or buffer which is involved in the modification of information. Single capacity theories, however, only account for part of the findings in the literature. Numerous studies have found that there is indeed minimal or nil trade-off between storage and processing. Consequently, alternative accounts have proposed that there are multiple components within working memory which will be discussed in the next section.

1.4.2 Theories that Support Multiple Components

The relative lack of dual-task disruption seen with particular task combinations has been linked to the operation of a multiple-component working memory system thought to offer online processing and temporary storage of information by means of a number of specialized cognitive functions (Baddeley, 1986; Baddeley & Logie, 1999). Within a multiple component model, each task is believed to draw specialized resources for visuospatial and verbal processing and storage (Baddeley et al., 1991). This perspective proposes that it is the types of tasks combined rather than the overall cognitive demand of the dual-task requirement that determines performance reduction in working memory (Cocchini et al., 2002).

Several studies have used combinations of processing and storage tasks to examine the influence of dual-tasking on working memory capacity (Cocchini et al., 2002; Duff & Logie, 2001; Friedman & Miyake, 2004; Maehara & Saito, 2007; Saults

& Cowan, 2007; Towse, Hitch, & Hutton, 2000). Cocchini et al. (2002) conducted two experiments, in which participants were required to perform pairwise combinations of a verbal memory task or a visual memory task with either a perceptuomotor tracking task (Experiment 1) or an articulatory suppression task (Experiment 2). They found minimal disruptions when two tasks were combined. Interestingly, there was a drop in accuracy when articulatory suppression was combined with a verbal memory task but not with the visual memory task. Based on these findings, Cocchini et al. concluded that a multiple component working memory model provided a better account of performance in concurrent immediate tasks than either models that assume a single capacity system for processing and storage or a limited capacity attentional system combined with active memory traces.

Duff and Logie (2001) conducted two experiments that examined the nature of working memory involved in span tasks using a version of the sentence span task (Daneman & Carpenter, 1980). In Experiment 1, participants verified sentences to determine whether the sentence was plausible and remember the final word of each sentence for later serial recall. Before the combined task, participants were required to perform each component of the task on its own. They found an overall decrement in both memory span and verification span when these tasks were performed together but suggested that this was due to an increased load on the central executive. In Experiment 2, Duff and Logie (2001) decreased the degree of integration within the general procedure: the processing task used arithmetic verification, whereas the memory task involved the recall of unrelated words. They argued that if performance was supported by a single flexible resource, then a less integrated task should require more resources for time sharing. Again they found only a small drop in performance in the combined task condition. They suggested that overall their results supported the multiple component models and argued that the central executive coordinates combined task performance as well as dealing with processing. The overall drop in performance on the two tasks can be attributed to an increase of load imposed on the executive by coordination. The alternative, from the single resource perspective, is that if both the processing and storage demands stretch working memory to its limits, then combining the task elements should result in a substantial drop in performance, greater than that observed in the experiments.

The storage-processing relationship has been examined by manipulating the processing requirements on storage activities and the role of storage on processing activities (Friedman & Miyake, 2004; Maehara & Saito, 2007). These have used the stimulus order effect, whereby the set of processing operations is held constant, and the completion order of individual activities is varied (Towse et al., 2000). Typically in these studies a trial comprised of either a short-duration task as the first activity and a long duration task as the last activity, or vice versa. This allowed the retention interval to be varied while the overall processing requirements of the task were kept constant. Towse et al. (2000) prepared mixed lists of short and long sentences and made short-final and long-final lists for their working memory span tasks. They found lower span scores for the long-final lists than for the short-final lists. They suggested that participants switch attention flexibly from the processing to the storage task requirements and then back again. They argued that a single-capacity model (like the one proposed by Just & Carpenter, 1992) could not fully explain the stimulus order effect because the same amount of processing was required in the short-final and long-final list. Overall, both lists had the same processing requirements, thus the only difference between the two was the temporal structure.

More recent research has contradicted the findings of Towse et al. (2000) by distinguishing between mechanisms involved in forgetting and storage/maintenance. Maehara and Saito (2007) used the stimulus order effect in addition to the processing time effect to examine the specific predictions from the representation-based interference account of working memory span. The representation-based account suggests that the nature of the material used in processing and storage episodes is critical in determining the magnitude of the stimulus order effect due to the interference of similarly attributed representations. They found that when items were from the same domain, the representations generated during the processing tasks interfered with the memory representations. Further, they found that the processing time effect in verbal-verbal and spatial-spatial working memory span tasks was consistent with the prediction of the representation-based interference account. However, inconsistent with the representation-based interference account they also found a processing-time effect in the verbal-spatial and spatial-verbal working memory span task. These results suggested that forgetting mechanisms in the working memory span tasks were domain specific. They also argued that storage or maintenance activities require attentional control and seem to involve domain-general properties as demonstrated by their findings on the processing time effect. Such activities may interrupt or interfere with processing activities. In contrast to Towse et al. (2000) who suggested a multiple component theory, Mahera and Saito (2007) proposed a more hybrid theory of working memory which incorporates both single and multiple capacities. Thus, the ability to recall information is domain specific but there is a central processor that is influenced by processing time.

Despite extensive research into the relationship between processing and storage there is little consensus on whether both activities are performed by a single mechanism or multiple mechanisms. Although most studies acknowledge that there is at least a small dual-task decrement, the underlying reasons may be due to the difficulty in coordinating processing and storage requirements (multiple component theories) or due to additional processing demands on a single capacity system (single component theories). What is clear regardless of theoretical orientation, is the importance of attention. Attention is central to both central resource and multiple capacity theories as is the concept of cognitive control. This will be discussed in detail in the upcoming section.

1.5 Task-Switching and Working Memory and its Relationship to Cognitive Control

A student sits in his room writing his doctoral thesis; he is thinking about the next three papers he needs to include in his literature review. He finishes a sentence and realises that he has misplaced one of the papers he needs to reference. He starts searching through the mess that is on his desk. His phone rings; it is a friend discussing plans for later that evening. In this example, there are numerous processes at work: the writing of a sentence, sequencing of subsequent papers to be added in the thesis, visual scanning, trying to recall where the paper was, answering the phone and considering plans for later on in the evening. Although most of these tasks in themselves are not difficult, the difficulty arises through switching attentional resources between tasks and reflects a load on cognitive control (also referred to as executive control; Logan, 2003); processes that control and coordinate skills, allows one to choose among tasks, monitor and adjust performance, and change tasks if required. These processes are also said to involve working memory.

Before examining the relationship between task-switching and working memory, it is important to understand the processes involved in switching between tasks. The ability to switch flexibly between tasks allows people to adapt to changing demands in the environment (Logan, 2003). However, task-switching comes at a cost. Switching set takes time and produces interference, as is evident in a variety of procedures that compare performance when tasks change, with performance when tasks remain constant (Allport, Styles, & Hsieh, 1994; Gopher, Armony, & Greensphan, 2000; Logan & Bundesen, 2003; Rogers & Monsell, 1995). The measurement of ‘switch costs’ is of interest because it may reflect the control processes that are engaged when individuals switch between two competing tasks. In task-switching experiments, the reaction time (RT) switch cost is typically measured as the difference in RT between switch and non-switch (repeat) trials (Wylie & Allport, 2000).

The interpretation of switch costs is controversial. Many researchers interpret switch costs as reflecting the time required to reconfigure the cognitive system. However, they disagree on what is involved during reconfiguration. In his theoretical paper, Monsell (2003) suggested three factors were associated with task switch costs: task-set reconfiguration costs, transient task-set inertia, and associative retrieval. The time taken to change tasks can be in part determined by task-set reconfiguration (TSR), a change in set that must occur before task-specific processes can proceed. This can include shifting attention between stimulus attributes or between conceptual criteria and retrieving information regarding task demands (Monsell, 2003). Transient task-set inertia refers to the carry over effect (or residual cost) of task-set activation from trial to trial. Evidence for this is seen in slower responses on the last trial of sequence A, B, A versus sequence C, B, A (Mayr, 2002; Mayr & Keel, 2000). Finally, associative retrieval refers to the fact that even when performing only one task, responses are slower if individuals have performed another task afforded by the same stimuli in the previous few minutes. This has been attributed to associative retrieval of task-sets that are associated with the stimulus (Monsell, 2003).

The task-switching paradigm is therefore commonly used to examine cognitive control. The difference in performance between switch and repetition trials (in mixed-task blocks) and single-task trials (in pure blocks) is called alteration cost. Rubin and Meiran (2005) examined the factors that result in poor performance in mixed-blocks when compared to pure blocks. They conducted two experiments exploring the origins of mixing costs. Participants performed either cued shape or cued coloured tasks or switched between the two within a trial. Experiment 1 examined the role of task ambiguity in mixing costs. They found that mixing costs only existed with ambiguous stimuli and not with stimuli used in one task. They argued that these tasks supported the hypothesis that mixed-task trials require the resolution of task ambiguity seen in situations where more than one type of task is present. An alternative explanation of mixing costs is that the working memory load is higher in mixed blocks because more than one condition is being activated in readiness at once. In a second experiment, Rubin and Merian (2005) examined the influence of working memory demands on mixing costs by adding stimulus-response rules. They aimed to load working memory in a manner that did not result in an increase in ambiguity. They found that holding different task sets in working memory did not influence mixing costs. This suggested that the transient competition between task sets during set selection is a critical factor in controlling task sets and thus contribute to mixing costs, whereas working memory demand did not (see also, Kray & Lindenberger, 2000; Los, 1996; Meiran, Chorev, & Sapir, 2000).

Working memory and task-switching are explicitly linked and require the flexible allocation of attentional resources. Several models of working memory have acknowledged the importance of attention (Baddeley, 2000; Cowan, 2005; Lavie, & De Fockert, 2005; Lavie, Hirst, De Fockert, & Viding, 2004). These include the episodic buffer introduced by Baddeley (2000) as an adjunct to his working memory model and Cowan’s (2005) postulation that an individual’s attention is flexible and can adjust from holding a single task goal to holding up to four objects or chunks of independent information. Several accounts assume that reconfiguration of information only involves processes that operate on working memory: changing the content of working memory is sufficient to change performance (i.e. changing goals and changing stimulus-response mapping rules; Mayr & Kliegl, 2000; Rubinstein, Meyer, & Evans, 2001; Sohn & Anderson, 2001). Other researchers argue that reconfiguration involves both processes outside of and within working memory. Changing goals is not sufficient; the subordinate processes must also be reprogrammed (Logan & Gordon, 2001; Meiran, 2000). Still others argue that switch costs reflect long-term memory processes that are outside of working memory. That is, switch costs reflect interference from past task sets or past associations to the stimuli under different task sets (Allport et al., 1994; Allport & Wylie, 2000). Although only an emerging field, examining the relationship between task-switching and working memory allows researchers to investigate the influence of cognitive control of attention on working memory.

Several studies have found that advanced preparation for an upcoming task reduces the magnitude of switch costs (Altmann, 2004; Mayr & Kliegl, 2000; Yeung & Monsell, 2003). Mayr and Kliegl (2000) examined the processes used to prepare for an upcoming task set. The main goal of their study was to specify and test the hypothesis that long-term memory retrieval is associated with task-switching and specifically with the proactive reconfiguration component. To achieve this, they made inferences about switch-related processes through specific interactions between the switch manipulation and manipulations of primary task demands. Specifically, they predicted that switch costs would increase as a function of primary-task retrieval demands. Overall, the results from this series of experiments suggested that the retrieval-demand effect on switch costs was specifically associated with the preparatory switch component. Mayr and Kliegl (2000) suggested that switch costs were larger when the switched-to task itself entailed high long-term memory retrieval demands (i.e. episodic retrieval) than when long-term memory retrieval demands were low (i.e. semantic retrieval). They concluded that the retrieval demand effect was selectively eliminated when people were allowed sufficient time for preparation. Thus, long term memory retrieval can be associated with the proactive or endogenous component of task-switching identified by Rogers and Monsell (1995) and Meiran (1996).

Expanding on previous research, Mayr and Kliegl (2003) proposed that two distinct, serial processing stages are critical during changes of task configurations. The first stage is associated with cue-driven retrieval of rules for upcoming task demands from long-term memory into working memory (i.e. retrieval stage). The retrieval stage can be triggered through any internal or external signal and it can be anticipated before the response relevant stimulus appears. The second stage is linked directly to the actual stimulus rather than to the task cues. During this stage, task rules are applied in a relatively automatic manner once the stimulus is presented.

To examine the distinction between these two stages, Mayer and Kliegl (2003) used the information reduction method. The key element of the information-reduction paradigm, as applied to the task-switching situation, is a 2:1 mapping between cues and tasks. When tasks can be accessed through more than one cue, three different types of trial-to-trial transitions are possible: (a) the task set and the cue stay the same (which is the usual no-switch condition); (b) a task switch is accompanied by a cue switch (which is the usual switch condition); or (c) a task set is repeated across successive trials, but the cue changes. They found that a large proportion of total switch costs was due to cue changes. Further, they found cue-switch costs but not task-switch costs were sensitive to effects of both practice and preparation. In contrast, task-switch costs were particularly sensitive to response-priming effects and task-set inhibition. They proposed that two processing stages occur during task-set selection: a cue-based retrieval of task rules is indexed by the cost associated with trial-to-trial changes in task cues without accompanying changes in tasks and a process that requires the application of active task rules to a stimulus and is indexed by the additional cost observed when both cues and tasks changed.

Central to the influence of task-switching on working memory is the role of sequencing. The coordination of multiple processes in a sequence plays an important function in understanding cognitive control (Schneider & Logan, 2006). Hierarchical control is present in the relationship between the sequence level (the representation of the task sequence and the processes that act on it) and the task level (the representations of the individual tasks and their component processes). Neither need hierarchical control in themselves but the relationship between the two needs to be hierarchical whereby the sequence level determines what happens at the task level.

Schneider and Logan (2006) investigated the relationship between sequence and task-level processing in the performance of a sequence of memorised tasks. In their study, participants were required to perform an arbitrary sequence consisting of two tasks without any relation to an overall goal. They assumed that a hierarchical control structure acted as an organized representation of control elements. Thus, participants were given a list of unrelated tasks and asked to perform a sequence iteratively. At the start of a block of trials, individuals memorised a task sequence involving task switches and task repetitions (e.g. A B B A). The sequence was then performed repeatedly during the block on a series of stimuli. In four experiments, switch costs in task-switching performance were manipulated by sequence initiation times that varied with sequence complexity, preparation time and type of sequence transition (repetition or switch). Hierarchical control was inferred from sequence initiation time effects. They found no switch costs at the first serial positions across sequences, that is, the point at which sequence-level processes are likely active in the initiation and maintenance of a hierarchical control structure in working memory. They concluded that complex patterns of behaviour often unfold according to plans and that hierarchical control of cognitive processes is involved in experiments requiring the performance of explicit, memorized task sequences.

An important factor in separating the cost of performing a task-specific switching program from that of maintaining it is offered by the distinction between endogenous (where the person needed to remember to switch) and exogenous control (where there was an obvious cue to switch; Rogers & Monsell, 1995). When a switch is signaled by a well-learned external cue then there is presumably no need to hold a task-specific program. The difference between the endogenous and exogenous conditions should be in the cost of maintaining and operating such a task-specific program (Baddeley, Chincota & Aldam, 2001). Diverting attention from one task to another is part of a larger system of cognitive control. The capacity to store and operate a complex program or set and the capacity to switch tasks are in theory, separable issues (Baddeley et al., 2001).

Baddeley et al. (2001) used a simple list based task-switching paradigm. The baseline condition used an exogenously cued version to study the process of switching. They then used this for studying the process involved under endogenous control, when the demands of switching were combined with the additional load of remembering the task-switching switch sequence. They found that switch costs increased when performing concurrent tasks and that impairment occurred for both blocked and switching conditions and that this occurred when a concurrent task had a central executive component. The second type of interference was most strongly associated with articulatory suppression, it had little impact on the blocked arithmetic condition but had a relatively clear effect in the switching condition. They suggested therefore that highly automatic verbal tasks such as simple articulatory suppression, or a well-learned response sequence such as counting, blocked the operation of the phonological loop while incurring minimal attentional demands. However, retrieval tasks that are attentionally demanding impacted on the capacity both to access simple number facts at speed and to retrieve the necessary operations involved in using an action control program.

Although many accounts of task-switching emphasise the importance of working memory as a substantial source of the switch cost, there is a lack of actual evidence supporting the proposition that task-switching places an additional demand on working memory. Liefgoofe, Barrouillet, Vandierendonck, and Camos (2008) conducted a series of four experiments in which they examined the effect of task-switching on working memory. In each experiment, participants were presented with time constrained tasks in which they had to switch between two digit judgements while remembering letters. They examined whether the number of switches impaired the concurrent maintenance of items. Their findings indicated little evidence for a strong relationship between task-switching and working memory. Although all four experiments indicated that task-switching impaired working memory maintenance, the size of the switch cost remained unaffected by the amount of information maintained. Liefooghe et al. (2008) argued that task-switching involved attention-demanding control processes and that working memory impairment was not mediated by processes specific to task-switching performance. Instead, they suggested that task-switching interfered with the maintenance of items in working memory because during switch trials, attention was occupied for a certain amount of time without the opportunity for compensatory activities. Consistent with previous research (Barrouillelt et al., 2004; 2007) switching interfered with maintenance of tasks and decaying memory traces could not be refreshed. Liefooghe and colleagues (Liefooghe et al., 2008) concluded that the effect of task-switching on concurrent maintenance of information in working memory did not necessarily rely on specific task reconfiguration processes but instead from a combination of simple and more fundamental attention demanding processes.

A formalised theory, encompassing the role of attention and the relationship between processing and storage is the Time-Based Resource-Sharing (TBRS) model. This unitary model of working memory was developed by Barrouillett et al. (2004) and assumes that both processing and maintenance of information within working memory require attention, a limited resource that must be shared. According to this model, cognitive cost is determined by a central bottleneck (Oberauer, 2003) whereby processing an activity has a negative effect on other concurrent activities. The TBRS model is based on the assumption that most of the working memory-span tasks, both processing and maintenance of information, rely on the same limited resource. Elementary cognitive steps involved in both processing and maintenance can take place only one at a time due to a central processing limitation (Barrouillett et al., 2004; Oberauer, 2003). These steps receive activation but when attention is switched away this activation suffers from a time-related decay. Attention can only be directed to one element at a time and the sharing of attention is achieved through a rapid and incessant switching of attention from processing to maintenance.

Despite the significant amount of research in this area, the relationship between working memory and task-switching remains unclear. What does seem apparent is that working memory tasks often require the flexible allocation of attentional resources. Given the importance of attention it may be that drawing attention away from a task will compromise performance and may account for switch costs. The research outlined here is somewhat limited by the types of methodology employed. The task-switching studies that have examined the nature of capacity limitations, processing and storage, and the relationship between task-switching and working memory have generally used separate tasks that have been performed in parallel. The task-span procedure (Logan, 2004) offers an alternative integrative approach to examining the relationship between task-switching and working memory. This will be discussed in detail in the next section.

1.6 Working Memory, Task-Switching and the Task-Span Procedure

The task-span procedure, developed by Logan (2004; 2007), was designed to examine the interaction between working memory and task-switching. In this procedure, individuals are given a list of tasks to perform and then a series of stimuli to perform them on. The task-span procedure requires working memory to store the list of task names and keep track of progress through the list. It requires task-switching because successive tasks on the list are generally different. It also requires subordinate processes, controlled by the executive, to perform the tasks on the list. The task-span procedure addresses several issues that distinguish theories of working memory, including the nature of capacity limitations, the nature of information loss, and the role of long-term memory in working memory spans.

In Logan's work, the task-span procedure involved three tasks that could be performed on numbers that were presented either as digits (e.g. 3) or words (e.g. nine). The three tasks were magnitude judgments (i.e. is the number greater than or less than 5), parity judgments (i.e. is the number odd or even), and form judgments (i.e. is the number a digit or a word). Task name reflected the alternative decisions within each judgment and each was mapped onto responses keys. Thus, Hi-Low was the name for the magnitude task, Odd-Even was the name for the parity task, and Digit-Word was the name for the form task. Participants were given lists of 1-10 task names. The lists were constrained so that each task was usually different from the one before it and the one after it. Consequently, individuals were required to switch tasks before performing each judgment. The names on the list were presented one at a time and followed by target stimuli that were presented one at a time. There was one target for each name on the list. The target stimuli were the digits 1, 2, 3, 4, 6, 7, 8, and 9 and the words one, two, three, four, six, seven, eight, and nine. As is typical in studies of task-switching, these stimuli were ambiguous, such that all three tasks could be performed on each of the stimuli. This stimuli was then used to contrast memory span condition where individuals were given lists of task names followed by cues to recall the names to the perform condition where participants were given lists of task names followed by lists of stimuli on which to perform the task.

Logan (2004) conducted a total of 4 experiments to examine the relationship between working memory and task-switching. The aim of the first experiment was to examine the role of additional processing and task-switching on working memory capacity and consisted of three conditions. The single-task condition required the individual to perform the same task on each target while in the memory span condition, individuals were given lists of task names followed by cues to recall the names. The perform condition used the task-span procedure where participants were given lists of task names followed by lists of stimuli on which to perform the task. Logan (2004) found that recall accuracy was equivalent between the perform and memory span conditions suggesting that there was no trade-off between processing and storage. Further, reaction times were slower in the perform condition than in either the recall or the single-task conditions. Reaction times in the perform condition were slower than the sum of reaction times in the recall and single-task conditions. He attributed this to switch costs and suggested that the perform condition required an extra process beyond those required in the recall and single-task conditions. He concluded that these results were inconsistent with theories of task-switching which assume that changing goals in working memory is sufficient to enable a new task set and consistent with theories which assume that subordinate processes must be reconfigured.

Logan (2004) subsequently examined time-dependent decay and item-dependent interference by manipulating the time between trials in the test phase. Results from experiment 2 were consistent with experiment 1 whereby spans in the perform condition were essentially the same as the memory spans, suggesting that processing did not trade-off with storage. In addition, the time between trials had little effect on task-spans or memory spans, supporting item-based interference as a better explanation of loss from working memory than time-based decay. The reaction times in the test phase showed a pattern of scalloping suggestive of chunking that followed the pattern of List-Lengths. This pattern of reaction times examined in the third experiment aimed to determine whether the scalloped pattern in the reaction time data could be explained by chunking. Individuals performed the task-span procedure with either consistent or varied lists. With consistent lists, they saw the same list of tasks for 10 consecutive study-test trials before proceeding to the next list. Under these conditions, they were expected to learn the sequence of tasks on each list in order to retrieve the next task directly from long-term memory, without having to retrieve chunks from working memory. With varied lists, individuals saw a different list on each study-test trial so they could not benefit from learning previous lists. Logan (2004) found that the scalloped pattern in function relating reaction times and list position appeared only in the varied-list condition and he argued that this supported the chunk retrieval hypothesis.

The final experiment was designed specifically to examine the minimal to nil trade-off between task-switching and storage. The task-span procedure was modified to manipulate the number of task switches participants had to perform. As before, participants were given lists of two, four, or six tasks. The novel requirement was that they had to perform each task several times. Participants in the alternating-task condition performed the tasks in sequence, two, three, or four times. Participants in the repeating-task condition performed each task on the list two, three, or four times before switching to the next task on the list. Logan (2004) found task-spans were unaffected by the amount of task-switching required. Task-spans were the same for participants who repeated tasks several times as for participants who alternated between tasks on every trial. Moreover, task-spans were the same regardless of the number of times the tasks had to be performed, which also determined the number of task switches that were required. He argued that storage in working memory does not trade-off with the executive processing required for task-switching.

Overall, the experiments suggested there was no trade-off between processing and storage. Task-spans were equivalent to memory spans despite the fact that the task-span procedure required substantial amounts of task-switching. Nor were task-spans influenced by the amount of task-switching. Logan suggested that his findings were more consistent with item-based interference than with time-based decay. There was little difference between conditions when retrieval probabilities were plotted against the number of items on the list, but there were dramatic differences between conditions when retrieval probabilities were plotted against retrieval time. The scalloped pattern in retrieval times suggested individuals retrieved the lists in chunks from long-term memory instead of keeping the entire list active in working memory. Experiment 1 compared reaction times in the task-span procedure with the sum of reaction times in the memory span and single-task conditions and found a substantial difference, suggesting that task-switching requires more than changing goals or mapping rules in working memory. The results of the four experiments suggested that several executive processes underlie performance in the task-span procedure. The processes that underlie storage seem to be separate from the processes that underlie task performance, and task-switching appears to involve processes outside of working memory. Logan (2004) suggested that the data are more consistent with theories that assume multiple executive processes than with theories that assume a single executive.

Subsequent work by Logan (2006) demonstrated that switch cost was better measured in the perform condition (task-span procedure) when estimated by comparing reaction time on alternation and repetition trials. Further, he suggested that if individuals performed each task on the list twice; retrieval was only required for the first but not the second trial in each pair. He found that retrieval time estimated by comparing the reaction time on trials that required retrieval with trials that did not, was more valid than the reaction time in the memory span condition which was used in his original experiment.

1.7 Rationale for the Current Study

Despite the extensive literature on the nature of working memory, there is still very little consensus regarding the underlying processes, specifically the nature of capacity limitations, strategic factors influencing capacity, and the relationship between processing and storage. Tasks that have examined the relationship between processing and storage have shown mixed results. Some results have suggested that there is a trade-off between processing and storage and these results have been used to suggest that there is a central capacity or processing limit in working memory (Just & Carpenter, 1992; Newell, 1990). Others have suggested that there is no or minimal trade-off between processing and storage and therefore processing and storage are independent processes (Engle et al., 1999; Kane et al., 2001; Kieras et al., 1999). More recently researchers have shown a keen interest in the relationship between working memory and the ability to switch between various tasks. This emerging field examines the relationship between task-switching and working memory and allows researchers to examine the influence of cognitive control of attention on working memory (Logan, 2003; Logan, 2004).

Several studies have used the dual-task methodology to study the relationship between processing and storage. Recently, Logan (2004; 2006) devised the task-span procedure to examine the relationship between processing and storage and the relationship between task-switching and working memory. Although numerous studies have manipulated the storage component, few have specifically manipulated the processing requirements of tasks. Experiment 1 of the current study will examine the influence of processing difficulty on storage capacity. In addition to providing information about how processing difficulty influences storage in working memory, it will also extend knowledge regarding how processing difficulty influences the relationship between working memory and task-switching.

Organisational processes exert large effects on memory, both in remembering novel information over short intervals and in learning material over a longer term (Bower, 1972). Chunking is one type of organisational process whereby information is reorganised into familiar or regular structures which can sometimes improve working memory performance (Ericcson et al., 1980; Bor et al., 2004). In short-term memory tasks there are several ways to group items. These include temporal, rhythmic, and/or spatial structures which can be imposed either externally or by an individual's internalized strategies. Experiment 2 will manipulate the role of chunking on working memory capacity and task-switching by varying the number of task-types to be recalled within a sequence.

Given prior knowledge of an upcoming task, people often prepare ahead of time so that their performance on the task proceeds more smoothly. From this perspective, preparation can be interpreted as activating a set of mental structures in anticipation. The more time invested in such advance preparation, the faster and less error prone the resulting performance (Altmann, 2004; Mayr & Kliegl, 2000). This preparation benefit seems to extend to simpler tasks used to study cognitive control in the laboratory. The preparation benefit is not accounted for in the original task-span procedure as proposed by Logan (2004; 2006). There are three required components to perform the task-span procedure accurately: (a) retrieve the task name that is appropriate for the current stimulus, (b) engage the task set appropriate to the task name, and (c) perform the appropriate task on the target stimulus. In the original task-span procedure the first 2 components are completed in the interstimulus interval. Experiment 3 of the current study will use a modified version of the task-span procedure to examine the role of working memory load on the time taken to flexibly switch between tasks, improve the measure of the reaction time costs associated with task-switching and to reduce the influence of chunking by creating symbol-task pairs that will constitute chunks in themselves.

Overall, the present series of experiments will further examine the nature of working memory capacity. This thesis aims to integrate and test theories of working memory, by implementing established as well as modified paradigms. The overarching objective will be to examine the relationship between additional processing requirements, organisational factors such as chunking, and task-switching on the ability to hold information in working memory.

Preliminary Tasks

A pilot study was conducted before the construction of the current series of experiments. In addition, prior to commencing the first experiment, participants were required to complete two preliminary tasks. The motor control task was used to determine the influence of key position on performance. The single task was used to examine the time taken to complete each of the tasks. The results from these two tasks were then used across all three experiments.

2.1 Pilot Study

2.1.1 Aim

The aim of the pilot study was to examine whether there was a difference in accuracy or reaction time when comparing the six tasks used in the current series of experiments.

2.1.2 Methods

2.1.2.1 Participants

Five individuals (2 males, 3 females) aged between 18-35 years (mean=25.60; sd=2.19) participated in the pilot study. They consisted of undergraduate and postgraduate students from Victoria University who volunteered their time.

2.1.2.2 Apparatus and Stimuli

The experiment was conducted in a sound and light attenuated room. The light in the room was such that the keys were visible but there was no reflection off the screen. All stimuli were presented using Presentation version 9.9, a stimulus delivery and control program. Response accuracy and reaction time (measured in tenths of a millisecond) were recorded for analysis.

All stimuli were presented using an IBM Celeron D and presented on a 17-inch monitor with 1024 x 768 pixel resolution. A Belkin personal computer keyboard was used to record all responses. Twelve keys were assigned to each type of response (Figure 1). The keyboard was modified to have the response keys placed in a central location and it was also elevated to allow the response keys to be clearly viewed by participants. Each response key had a label placed on it; the label was the first letter of each potential decision (i.e. High was represented by H, Low was represented by L etc.). Each key was mapped so that the first half of the decision pair was positioned above the second part of the decision pair (i.e. on the keyboard, the High key was above the Low key). All other keys not used directly in this series experiment were covered to reduce interference. Response key positions were counterbalanced across participants so that for 50 percent of the participants, left to right, the keys were High/Low, Odd/Even Digit/Word, Red/Green, Big/Small, and Above/Under (Figure 1, Version A) and for the other 50 percent of participants they were ordered Above/Under, Big/Small, Red/Green, Digit/Word, Odd/Even, and High/Low (Figure 1, Version B).

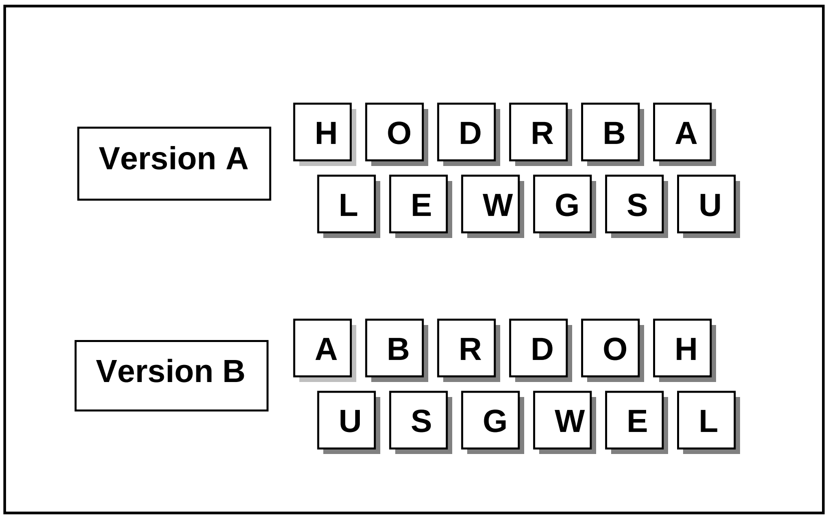

Figure 1. Keyboard layouts for both Version A and Version B in Experiments 1, 2 & 3; H=High, L=Low, O=Odd, E=Even, D=Digit, W=Word, R=Red, G=Green, B=Big, S=Small, A=Above and U=Under.

Each task could be performed on numbers that were presented as either digits (e.g. 3) or words (e.g. three). The tasks included magnitude judgements (i.e. is the number greater than or less than 5); parity judgments (i.e. is the number odd or even); form judgments (is the number presented as a digit or a word); colour judgement (i.e. is the colour of the number red or green); size judgment (i.e. is the font size of the stimulus big 48 point or small 24 point); position judgement (i.e. is the number presented above or under the centrally placed shape).

2.1.2.3 Procedure

Participants were given 6 blocks of trials. At the start of each block**,** participants were given instructions for a single task. Participants were then presented with numbers, either digits or words, on which they were required to make an appropriate decision. Each number was presented for 3000ms or until a response was registered. Responses were made using one of two buttons that corresponded to the two potential decisions in each block. For example, in the Odd/Even condition participants were required to press the O key if the number presented was odd and the E key if the number presented was even. Each participant was given 5 practice trials per condition for a total of 30 practice trials. There were 100 trials per task type in the pilot study for a total of 600 trials.

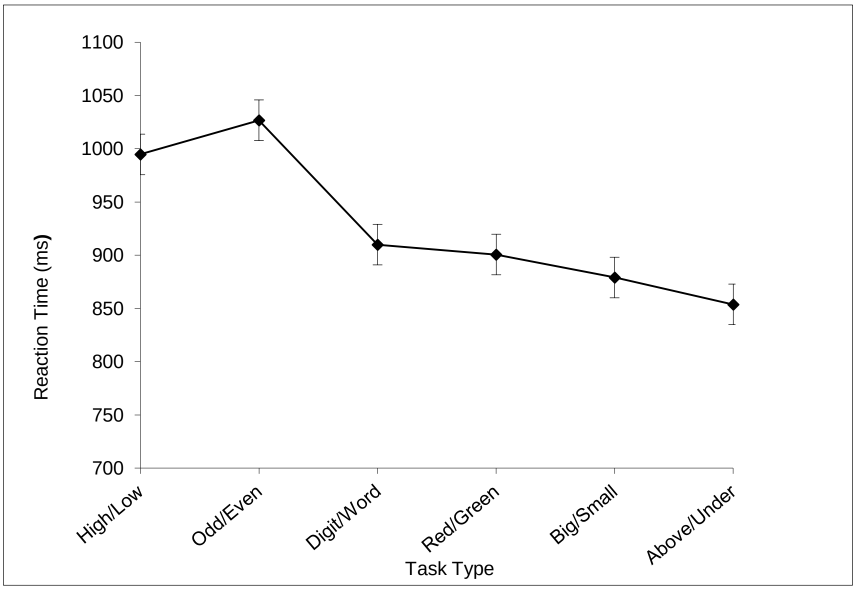

Figure 2. Mean reaction time (ms) and standard error for High/Low, Odd/Even, Digit/Word, Red/Green, Big/Small and Above/Under.

2.1.3 Results and Discussion

All data analysis was conducted using the computer program Statistical Package for the Social Sciences (SPSS; Version 15.0). A one-way ANOVA revealed that there was a significant difference in reaction times between the tasks, $F_{(1,5)}=7.27$, $p<.001$. Post hoc analysis using Tukey's HSD revealed that the High/Low task was significantly slower than the Big/Small and Above/Under conditions. Further the Odd/Even task was significantly slower than the Digit/Word, Red/Green, Big/Small and Above/Under conditions (Figure 2). These findings suggested that the High/Low and Odd/Even tasks were the most difficult in that they took the longest to complete and supported the distinction between easy and hard tasks. There was no difference across tasks in accuracy.

2.2 Motor Control Task

2.2.1 Aim

The motor control task was designed with two purposes. First, to familiarise participant with keys that were to be used in subsequent tasks and second, to measure the reaction-time differences between response keys.

2.2.2 Method

2.2.2.1 Participants

16 individuals (7 males, 9 females) aged between 18-35 years (mean=26.44; sd=3.05) participated in the experiments. They consisted of undergraduate and postgraduate students from Victoria University who volunteered their time. All participants gave informed consent (Appendix A and B). Participants were required to have normal or corrected-to-normal vision.

2.2.2.2 Apparatus and Stimuli

The apparatus used in the motor control task was identical to the pilot study. The motor control task involved 12 words being presented on the computer screen. Each word was white and presented on a black background in Times-New Roman font, 48 font size. Each word was positioned in the centre of the screen. The words were High, Low, Odd, Even, Digit, Word, Red, Green, Big, Small, Above, and Under.

The words presented in the motor control task were representative of choices that would be made in subsequent experiments.

2.2.2.3 Procedure

Participants were seated in front of the computer screen at a distance of 57cm with their head placed in an adjustable chin rest so that their eye line was at the centre of the screen. They were instructed to make their choice response by pressing keys on a modified keyboard using their dominant hand. A small coloured pad was placed 5 cm from the base of the keyboard which participants were required to return their hand to after each word was displayed and a response had been made. Response keys were counterbalanced across participants.

At the beginning of each trial, the word 'Ready' was presented on the computer screen. Participants were required to press the space bar to begin the trial. This was followed by an interstimulus interval of 500ms and was subsequently followed with a word. Each task name was displayed for 2000ms or until a response was registered. Participants were required to press the key which corresponded to the first letter of each of the twelve words. Thus, the keys were: H=High, O=Odd, D=Digit, R=Red, B=Big, A=Above, L=Low, E=Even, W=Word, G=Green, S=Small and U=Under. Following each response, participants were required to return their hand to the coloured pad in preparation for the next trial; there was a 500ms gap which allowed participants to do this without detriment to their response times.

The presentation order was randomised and each word was presented ten times so that there were a total of 100 trials per block of trials. Keys positions were counterbalanced so that half of the participants had the keys placed in configuration A and half of the participants had the keys in configuration B (Figure 1).

2.2.3 Results and discussion

A one-way ANOVA was conducted to examine whether there were any significant differences in the reaction times between the response keys. Analysis revealed no significant difference between any of the response keys. Given the non-significant results no adjustments were made in the subsequent experiments.

2.3 Single-Task

2.3.1 Aim

The single task condition was used to compare the time taken to complete each of the 6 tasks that would be used in subsequent experiments.

2.3.2 Method

2.3.2.1 Participant, Apparatus, and Stimuli.

The participants and apparatus were identical to that described in the motor control task. Each task could be performed on numbers presented as either digits (e.g. 3) or words (e.g. three). The tasks included magnitude judgements (i.e. is the number greater than or less than 5); parity judgments (i.e. is the number odd or even); form judgments (i.e. is the number presented as a digit or a word); colour judgement (i.e. is the colour of the number red or green); size judgment (i.e. is the font size big 48 point or small 24 point); position judgement (i.e. is the number presented above or under the centrally placed shape).

2.3.2.2 Procedure

Participants completed 6 blocks of trials. At the start of each block, participants were given instructions for a single task. Participants were then presented with numbers, either digits or words, on which they were required to make an appropriate decision. Each number was presented for 3000ms or until a response was registered. Responses were made using one of two buttons that corresponded to the two potential decisions in each block. For example, in the Odd/Even condition participants were required to press the O key if the number presented was odd and the E key if the number presented was even. Each participant was given 5 practice trials per condition for a total of 30 practice trials. There were 40 trials per task type in the single task condition for a total of 240 trials.

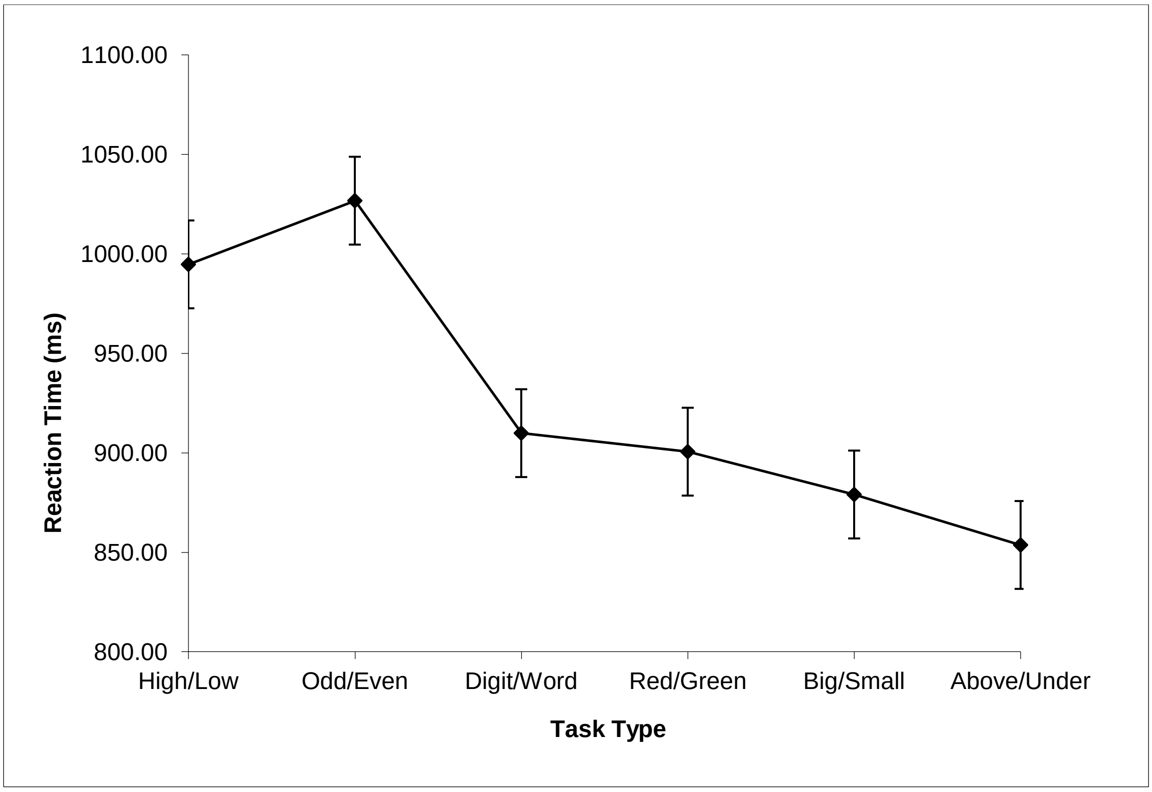

Figure 3. Mean reaction times (ms) and standard error for the single task condition

2.3.3 Results and Discussion

Mean reaction time were calculated for each participant (Figure 3). A one-way ANOVA revealed that there was a significant difference in reaction times between the tasks, $F_{(1,15)}= 9.37$, $p<.001$. Post hoc analysis using Tukey's HSD revealed that the High/Low task was significantly slower than the Red/Green, Big/Small and Above/Under conditions. Further, the Odd/Even task was significantly slower than the Digit/Word, Red/Green, Big/Small and Above/Under conditions (Figure 1). These findings were consistent with the pilot study and suggested that the High/Low and Odd/Even tasks were the most difficult such that they had longest reaction times; this supported the distinction between easy and hard tasks. In addition, individuals' reaction times for single tasks were used for the combined condition in experiments 1, 2 and 3.

Experiment 1

3.1 Aims and Hypotheses

The aim of Experiment 1 was twofold; firstly to replicate the work of Logan (2004) and secondly to examine the role of increased processing costs on working memory capacity using the task-span procedure. Experiment 1 assessed the trade-off between processing and storage by comparing the recall of task sequences (memory span condition) with a task that required both the recall and completion of tasks (perform condition). Further, it aimed to gauge the role of reconfiguration of subordinate processes in task-switching by comparing reaction times in the perform condition with the sum of reaction times in the recall condition and the single-task condition.

Results from the pilot study revealed that reaction time in both the High/Low task and Odd/Even task were significantly slower than all of the other judgements. Based on these findings, there were two groupings of tasks in Experiment 1, hard and easy. The hard condition consisted of three tasks; High/Low (i.e. is the number greater than or less than 5), Odd/Even (i.e. is the number odd or even) and Digit/Word (i.e. is the number a digit or a word) and was consistent with the tasks used by Logan (2004). The easy condition consisted of three tasks; Digit/Word (i.e. is the number a digit or a word), Big/Small (i.e. is the font size big or small) and Red/Green (i.e. is the colour of the number/word either red or green) these were the three tasks with the fastest reaction time in the pilot study. It was hypothesised that RTs would be significantly faster for the easy condition than for the hard condition.

Given the reaction time difference between tasks in the pilot study it was also predicted that the hard span task combination would lead to reduced accuracy compared to the easy span task combination.

Based on Logan's (2004) findings it was predicted that RTs in the perform condition would be significantly slower than the combination of the single task and memory span condition and that these additional reaction time costs would be related to the cost of task-switching.

Based on previous research (Logan, 2004), it was predicted that there would be no difference in accuracy between tasks that required only the recall of task sequences (memory span condition) and tasks that required both the recall and completion of tasks (perform condition) .

3.2 Method

3.2.1 Design

In Experiment 1, a 3-way within-subjects repeated measures design was used. There were two levels of task-type (memory span or perform) , two levels of task difficulty (difficulty easy and difficulty hard) and three levels of List-Length (items in a list of stimuli 4, 6, or 8). The two dependent variables in this experiment were reaction time (measured in milliseconds) and accuracy (proportion of correct trials).

3.2.2 Stimuli and Apparatus

The task-span procedure consisted of up to five tasks that could be performed on numbers that were presented as either digits (e.g. 3) or words (e. g. nine). The tasks were magnitude judgments (i.e. is the number greater than or less than 5), parity judgments (i.e. is the number odd or even), form judgments (i.e. is the number a digit or a word), size judgments (i.e. is the font size big or small), and colour judgments (i.e. is the font red or green).

The task names determined the response type. Thus, High/Low referred to the magnitude task, Odd/Even referred to the parity task, Digit/Word represented the form task, Big/Small was the name of the size task and Red/Green was the name of the colour task. Participants were given a list of four, six or eight task names. The lists were constructed in such a way that each task was different from the one before it and the one after it. The target stimuli included the digits 1-9 and the words one, two, three, four, six, seven, eight, and nine.

There were two groupings of task names; difficulty hard and difficulty easy. The hard condition involved sequences of three tasks of greater difficulty which was determined by reaction time differences during the single task condition and the pilot study. The three judgments in the difficulty changing grouping were: High/Low, Odd/Even, and Digit/Word. The difficulty easier condition involved sequences of three tasks all requiring form judgments and with lower difficulty across tasks. The three judgments in the difficulty easy grouping were: Digit/Word, Red/Green and Big/Small.

All stimuli presented were counterbalanced across non-relevant conditions (i.e. conditions not directly relevant to the task). Thus, 50 percent of the stimuli were presented as digits and the other 50 percent as words, 50 percent of the numbers presented were greater than five, 50 percent were less than five, 50 percent were odd and 50 percent were even, 50 percent were red and 50 percent were green, 50 percent were big and 50 percent were small.

3.2.3 Procedure

At the beginning of each trial, the word 'Ready' was presented on the computer screen. Participants were required to press the space bar to begin the trial. There were two parts to each trial; a study phase and a test phase. In the study phase, a sequence of task names was presented. Participants were asked to memorize the order of the task names because they were required to respond to them appropriately in the test phase. Each study list was preceded by a display "STUDY: Task List-Length *N*," where *N* was the sequence length in the study phase. Each task name appeared on screen for 1000 millisecond followed by an interstimulus gap of 1000 milliseconds before the next task name appeared. In the subsequent test phase, participants were presented with prompts. The prompts were either numbers (digits or words; in the perform condition) or position within a sequence (i.e. First, Second, Third etc.). During the test phase, each prompt was displayed for 3000 milliseconds or until a response was recorded. Participants were required to respond to the prompts by using the response key that either corresponded to the name of the task in the span condition or the correct response in the perform condition. All experiments involved two conditions: a *perform* condition that implemented the task-span procedure whereby individuals were given lists of task names followed by lists of stimuli on which to perform the tasks on; and a *recall* condition where individuals were given lists of task names and then cues to recall the names of the task.

Participants were given three practice trials each for the span and perform conditions to allow participants to become familiar with the flow of the experiment. There were 5 trials for each List-Length, for both the easy and hard conditions, and both the span and the perform conditions. Thus, in Experiment 1 the total number of trials was 60. Participants were also advised to remember the first word of each task pair as this would make it easier to remember the sequence and provide the opportunity for maximum performance.

3.3 Results

Mean RTs and proportion of correct trials were calculated for each participant in all experiments. Various repeated measures Analysis of Variance (ANOVAs) were conducted. All planned (a priori) contrasts were conducted using a bonferroni correction (Field, 2005) to reduce the family-wise error rate due to multiple comparisons. Dependent t-tests, using Bonferroni corrections, were also used to further investigate significant interactions. The assumption of sphericity was measured using Mauchley's test. The Huynh-Feldt correction was used as it is a more conservative measure of significance (Field, 2005).

3.3.1 Accuracy

The proportion of trials in which participants achieved 100 percent accuracy was calculated for each participant as a function of task type (memory span or perform), task difficulty (easy or difficult) and List-Length (4, 6, or 8). A 2x2x3 repeated measures ANOVA was conducted for proportion of correct trials. Pairwise comparisons were conducted using Bonferroni corrections. Figure 4 shows the mean proportion of 100 percent accurate trials for the memory span and perform conditions as a function of task difficulty and List-Length.

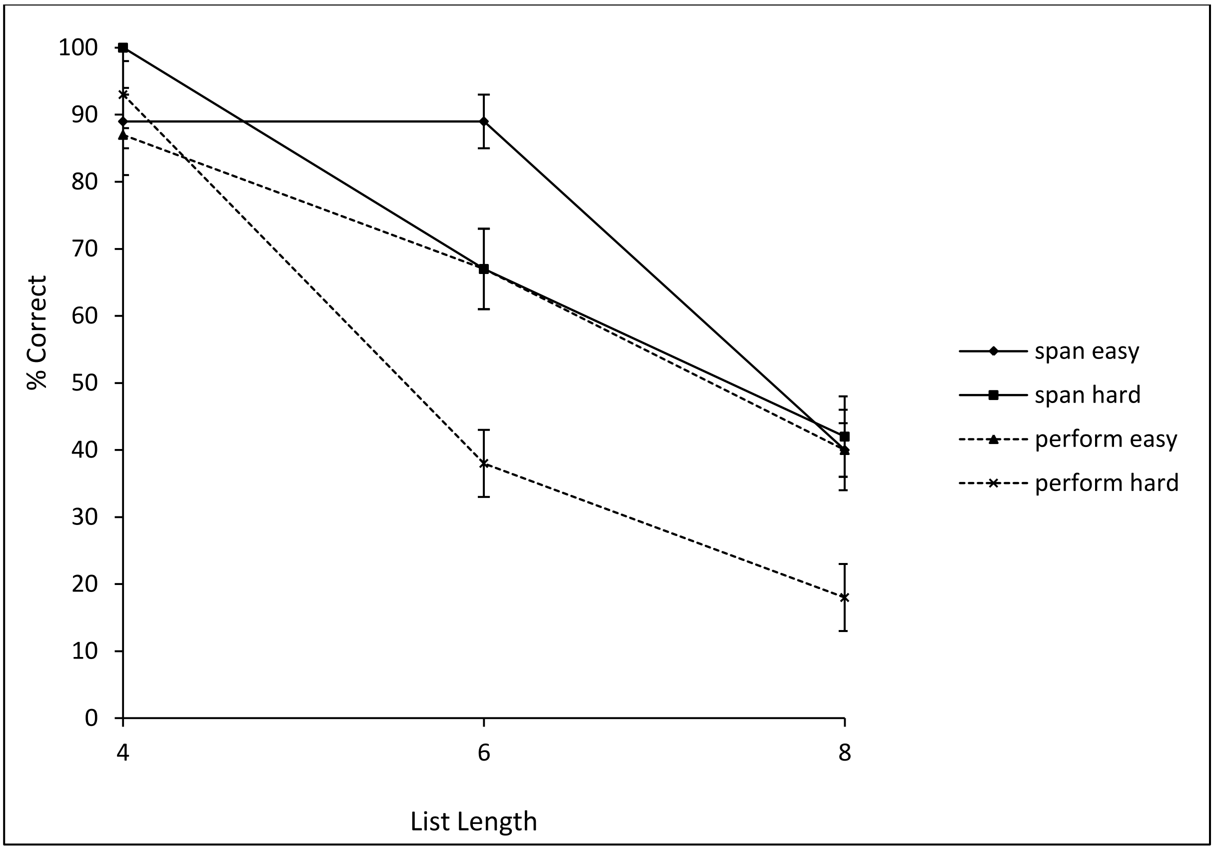

Figure 4. Proportion of 100 percent correct trials and standard error for memory span and perform conditions across List-Length and task difficulty.

There was a significant main effect for task type on proportion of trials 100 percent correct, $F_{(1,14)}$=19.84, $p<.01$ such that accuracy in the memory span condition was significantly higher than in the perform condition. There was a significant main effect for difficulty on the proportion of trials 100 percent correct, $F_{(1,14)}$=7.02, $p<.05$ such that accuracy in the easy condition was significantly higher than in the hard condition.

As expected, there was a significant main effect for List-Length, $F_{(1,14)}$=55.25, $p<.01$ such that accuracy for List-Length 4 was significantly greater than both List-

Length 6 and List-Length 8. Further, accuracy for List-Length 6 was significantly higher than that of List-Length 8.

A significant interaction was found between List-Length and task type, $F_{(1,14)}=3.34$, $p<.05$. Pairwise comparisons revealed that accuracy was significantly higher in the span List-Length 6 condition (M=0.77, SE=0.05) than in the perform List-Length 6 condition (M=0.52, SE=.06, $t_{(14)}= 3.28$, $p<.01$). Similarly, pairwise comparisons revealed that accuracy was significantly greater in the span List-Length 8 condition (M=0.41, SE=0.06) than in the perform List-Length 8 condition (M=0.29, SE=0.05, $t_{(14)}=2.92$, $p<.01$).

There was also a significant interaction between List-Length and task difficulty, $F_{(1,14)}=3.83$, $p<.05$. Pairwise comparisons revealed that accuracy was significantly greater for the List-Length 4 hard condition (M=0.97, SE=0.02) than the List-Length 4 easy condition (M=0.89, SE=0.03, $t_{(14)}= 2.48$, $p<.01$). Conversely, pairwise comparisons revealed that accuracy was significantly lower for the List-Length 6 hard condition (M=0.52, SE=0.06) than the List-Length 6 easy condition (M=0.78, SE=0.04, $t_{(14)}= -5.30$, $p<.001$).

Overall, these results suggest that accuracy was higher when participants were only required to recall items rather than when additional processing in the form of task completion was also required. Further, the results indicated that accuracy reduced as the number of tasks to be recalled increased. Finally, the results suggested that accuracy diminished after a certain processing threshold was reached in both the span and perform conditions, and easy and hard conditions.

3.3.2 Reaction Time

The mean reaction time for trials in which participants achieved 100 percent accuracy was calculated for each participant as a function of task type (memory span or perform), task difficulty (hard or easy), and List-Length (4, 6, or 8; see Figure 5). A 2x2x3 repeated measures ANOVA was conducted for mean reaction times of correct trials. Pairwise comparisons were conducted using Bonferroni corrections. Figure 5 shows the mean reaction times for 100 percent accurate trials for both the span and perform conditions as a function of task difficulty and List-Length.

There was a significant main effect for difficulty on mean reaction time, $F_{(1,14)}=10.77$, $p<.05$ such that reaction times in the easy condition were significantly faster than in the hard condition. There was a trend for task-type that approached significance, $F_{(1,15)}=4.91$, $p=.069$ such that reaction times in the memory span condition were faster than the perform condition. There was no main effect for List-Length.

There was also a significant interaction between task type and List-Length $F_{(1,14)}=6.58$, $p<.01$. Pairwise comparisons revealed that reaction times were significantly faster in the span List-Length 8 condition (M=1514.57, SE=45.61) than the perform List-Length 8 condition (M=1796.48, SE=78.09, $t_{(14)}= -3.74$, $p<.01$).

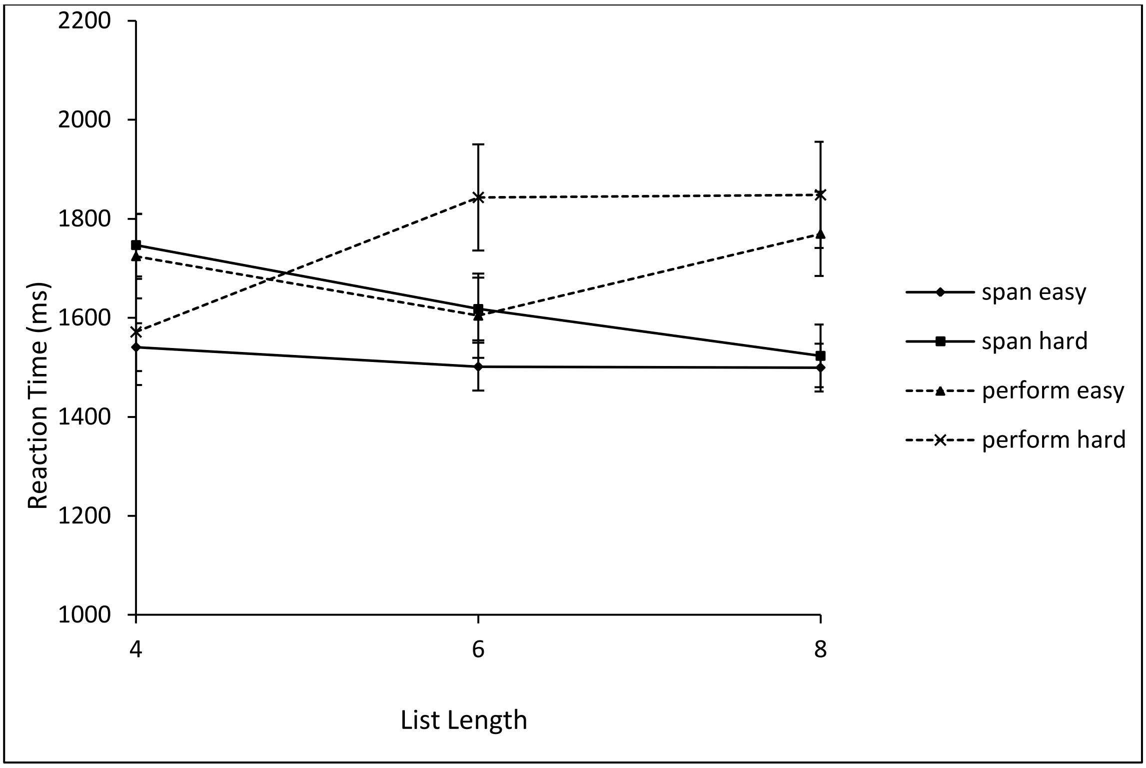

Figure 5. Mean reaction times (ms) and standard error for memory span and perform conditions across List-Length and task difficulty.

Overall, reaction time data showed that there was a trend in reaction times where times were faster (approaching significance) for the span condition than the perform condition. Reaction times were faster for easier groupings of tasks as compared to hard grouping of tasks. Finally, when storage was maximised (i.e. List-Length 8), reaction times were faster for tasks that required storage alone (span condition) as compared to storage and processing (perform condition).

3.3.3 Reaction Time Measure of Task-Switching

Further comparisons to examine the role of switch costs were conducted using the additive method developed by Logan (2004); an individual's single task RT was added to their memory span task RT and then compared to the perform RT to examine additional costs associated with switch costs beyond those of task performance. Again, the mean reaction time for trials in which participants achieved 100 percent accuracy was calculated for each participant as a function of task type (memory span or perform), task difficulty (hard or easy) and List-Length (4, 6, or 8; see Figure 6). A 2x2x3 repeated measures ANOVA was conducted for mean reaction time of correct trials. Pairwise comparisons were conducted using Bonferroni corrections. Figure 6 shows the mean reaction time for 100 percent accurate trials for both the memory span+single task and perform condition as a function of task difficulty and List-Length.

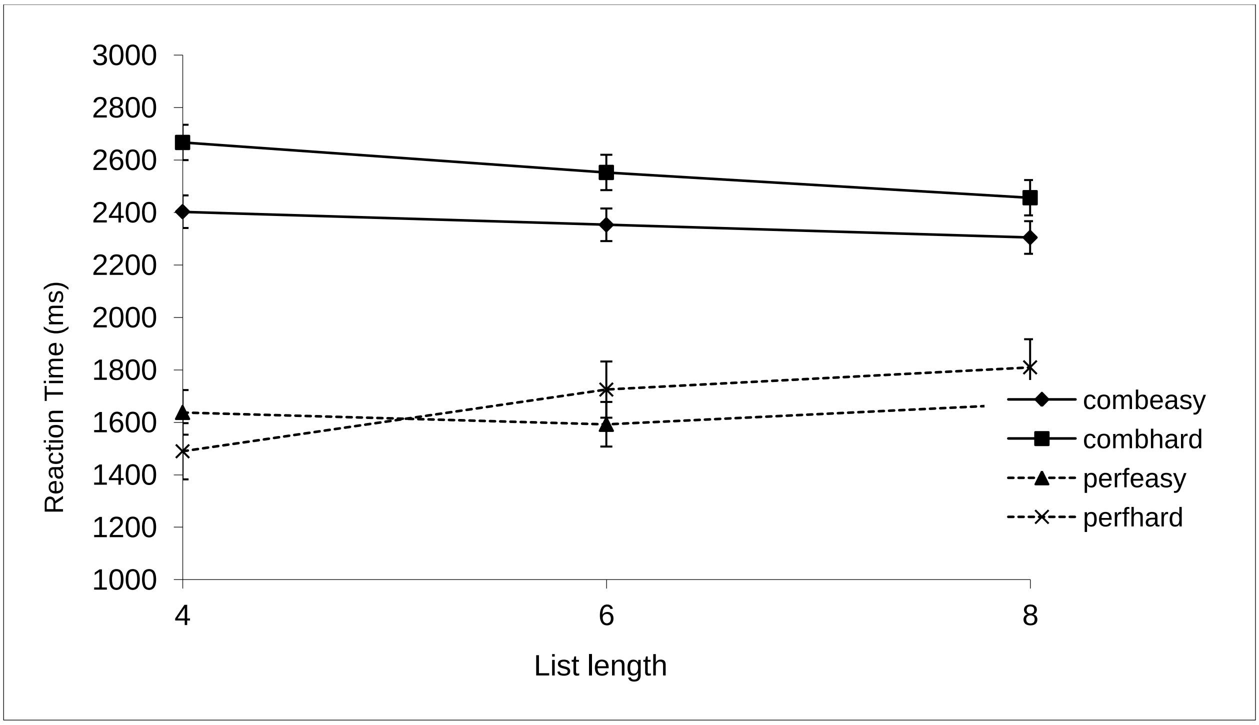

Figure 6. Mean reaction times (ms) and standard error for combined single task with memory span and perform conditions across List-Length and task difficulty

Analyses revealed a main effect for task type, $F_{(1,6)}=167.54$, $p<.001$ such that reaction times in the combined condition (memory span + single task) were significantly slower than the perform condition. There was a significant main effect for difficulty on mean reaction time, $F_{(1,6)}=24.47$, $p<.01$ such that reaction times in the easy condition were significantly faster than in the hard condition. There was no main effect for List-Length.

There was a significant interaction between task type and task difficulty $F_{(1,6)}=7.22$, $p<.05$. Pairwise comparisons revealed reaction times were significantly faster in the combined easy (memory span + single task) condition (M=2407.70, SE=56.49) than the combined hard (memory span + single task) condition (M=2601.75, SE=70.42, $t_{(1,15)}=-6.58$, $p<.001$). However, there was no significant difference between the perform easy and perform hard conditions.

There was a significant interaction between task type and List-Length, $F_{(1,6)}=11.45$, $p<.05$. Pairwise comparisons revealed that reaction times were significantly slower in the combined List-Length 4 condition (M=2560.87, SE=67.05) than the combined List-Length 6 condition (M=2493.80, SE=62.50, $t_{(15)}= 2.72$, $p<.05$). Further, reaction times were significantly slower in the combined List-Length 4 condition (M=2560.87, SE=67.05) than the combined List-Length 8 condition (M=2430.93, SE=62.41, $t_{(14)}= 3.63$, $p<.01$) and in the combined List-Length 6 condition (M=2493.80, SE=62.50) than the combined List-Length 8 condition (M=2430.93, SE=62.41, $t_{(14)}= 2.59$, $p<.05$). Reaction times were significantly faster in the perform List-Length 4 condition (M=1665.72, SE=96.19) than the perform List-Length 8 condition (M=1796.48, SE=78.09, $t_{(14)}= -2.33$, $p<.05$).

Contrary to expectations, the results indicated that there were no additional switch costs in the perform condition. Unlike Logan (2004), the perform condition was not slower than the combination of the single task and span conditions. In fact, the combined condition was significantly slower than the perform condition. The results also indicated that reaction times were faster in the easy span compared to the hard span in the combined condition. Finally, the results revealed a relationship between task type and List-Length whereby in the combine condition, reaction times increased as a function of List-Length. There was greater variability in the perform condition and this effect was not seen as consistently.

3.4 Discussion

The overarching aim of the first experiment was to examine the nature of capacity limits in working memory and its relation to both task-switching and task difficulty. The current experiment used the task-span procedure developed by Logan (2004). This procedure enabled the comparison of task performance alone, against a recall component and both of these against the requirement to recall and perform the task together. Further, this procedure allowed these conditions to be compared across both reaction time and accuracy. Experiment 1 had two components which were jointly based on Logan's (2004) work and findings from the pilot study (and again evident in the single task condition of the current study). The first condition was the hard condition which was a replication of Logan's work (2004) and consisted of the three most complex tasks. The second condition was the easy condition which consisted of tasks that were easier (the distinction between the easy and hard were based on reaction time data from the pilot study and the single task condition).

3.4.1 The Nature of Capacity Limits in Working Memory

Based on previous research (Logan, 2004), it was predicted that there would be no significant difference between tasks that required only the recall of task sequences (memory span condition) and tasks that required both the recall and completion of tasks (perform condition). The current study found that accuracy increased when participants only had to recall the task sequences (memory span) as compared to both recalling and performing the task sequences (perform condition). These findings were inconsistent with Logan's results (2004; Experiment 1). Logan showed a very small trade-off between accuracy and processing such that the memory span and perform conditions were essentially equivalent. He defined memory span as the maximum List-Length that can be recalled in order, perfectly, 50% of the time (Miller, 1956). By this criterion, the memory span was 6.9 items in the recall condition and the task-span was 6.2 items with strict scoring and 6.3 items with lenient scoring in the perform condition. The requirement to perform the tasks as well as recall their names reduced the memory span by 0.7 items—about 10 percent—suggesting a weak trade-off between processing and storage. The difference in accuracy between the span and perform conditions in the current experiment was significantly greater than that seen in Logan 2004 (Experiment 1) suggesting that there was a significant trade-off between processing and storage. At List-Length 6, accuracy in the span condition was 89 percent compared to 38 percent in the perform condition, a difference of 51 percent. Furthermore, at List-Length 8, accuracy in the span condition was 40 percent compared to 18 percent in the perform condition, a difference of 22 percent. The findings of the current experiment suggest that there is a significant trade-off between processing and storage.

In terms of reaction time, the results suggested that participants were significantly faster in the memory span condition versus the perform condition. However, this was expected given that the perform condition required not only the recall of the task but also the performance of a task; intuitively this additional requirement should produce a consistent RT difference between the memory span and the perform conditions across List-Lengths. RTs were expected to be consistently slower in the perform versus memory span condition. The current results showed that reaction times were significantly slower in the perform condition as compared to the memory span condition when the List-Length was 6 but this difference was not seen in the List-Length 4 condition. It can be argued that the distinction between span and perform is not seen in List-Length 4 as this difference only becomes apparent when the processing capacity of working memory is reached.

The variation in results between the current study and Logan (2004) could be explained, at least in part, by the influence of practice. Participants in Logan's study were given numerous trials over a number of days, while participants in the current study were only given a few trials during one testing session. It could be argued that Logan's participants were more familiar with tasks and these tasks may have been transferred into long-term memory. The involvement of long-term memory in the storage of task rules could indeed reduce working memory involvement in the task-span procedure. Familiarity with task rules is relevant in the perform condition as it requires the explicit recall of task instructions and these additional requirements would increase overall working memory load. Thus, higher accuracy would be expected when there is greater long-term memory involvement and consequently reduced working memory/processing load.

The role of practice in dual-task conditions is supported by the findings of Oberaur and Kliegl (2004) who argued that dual-task costs reduced when there was sufficient practice of combinations of tasks but not when two tasks were practiced independently. In Logan's (2004) work, additional trials over multiple sessions allowed the opportunity for a greater amount of practice and this meant that the recall of the task and the performance of the task (using task rules) had more opportunity to be practiced and therefore combined into a single task. This would cause a reduction in dual-task costs as shown by Logan however this finding was not supported in the current study. This suggests that the current methodology produced a more accurate measure of working memory capacity than Logan's methodology.

Another key difference between Experiment 1 and Logan's (2004) work was the number of task rules that participants needed to learn. In the current study, 5 sets of task rules were kept active within working memory compared to only three in Logan's (2004) study. Participants were required to learn three tasks for the hard condition and an extra two tasks for the easy condition. More representations combined with less practice trials in the perform condition (as discussed earlier) may have contributed to greater load on working memory. The influence of additional representations or task rules held in working memory and the interaction with List-Length will be further examined in Experiment 2.

Working memory can be defined either as a single cognitive resource that is used for both processing and storage (Anderson et al., 1996; Lovett et al., 1999) or as a group of dissociable cognitive functions that often act in unison according to task requirements (Baddeley, 1986; Baddeley & Logie, 1999; Cocchini et al., 2002). The trade-off between processing and storage seen in the current experiment supports previous research which has shown trade-offs between concurrent memory loads and executive processes involved in preparation for upcoming tasks (Logan, 1978, 1979), generating unique responses (Baddeley, et al., 1984), and manipulating stored items (Anderson et al., 1996). In the current study, both the accuracy and reaction time data supported previous research such that when working memory demand increased, by increasing the number of items held in memory span, there were more errors and slower reaction times (Anderson et al., 1996; Baddeley, 1986; Caplan et al., 1992).

The trade-off between processing and storage seen in the current experiment is consistent with the work of Colom and colleagues (Colom et al., 2006). Using the comparison between simple and complex span to examine the trade-off between processing and storage, Colom et al., (2006) proposed that there was a general component for maintaining information in an active state that was determined by the efficiency of working memory itself. Consistent with the present study, they found that the additional processing requirements lowered the reliability of temporarily stored information. That is, additional processing requirements remove a proportion of the capacity used for the maintenance of working memory traces. Colom and colleagues (Colom et al., 2006) suggested that concurrent processing requirements leave less capacity for temporary storage of information. This diminishes the reliability of the stored information, which consequently results in a greater number of errors. Similarly, in the current experiment the additional processing requirement as determined by the completion of the task within the perform condition shifted attention away from the memory traces. Consequently, accuracy of recall was reduced.

In further support of a single capacity theory, the current study found that the difference in accuracy between memory span tasks and perform span tasks was more prominent when working memory load was higher (at List-Lengths 6 and 8) rather than when it was lower (at List-Length 4). Thus, the trade-off between processing and storage was only seen when working memory load increased and participants were also required to perform the task. In the current experiment there was no significant difference in accuracy between the span and perform condition for List-Length 4, however there was for the List-Length 6 and List-Length 8 conditions whereby in both these conditions, accuracy was significantly higher for the span condition as compared to the perform condition. When comparing List-Length 4 to List-Length 6, reaction times were significantly slower in the perform condition than the span condition when the List-Length was 6 but not when the List-Length was 4. As with accuracy data, these results support a trade-off between processing and storage when a certain capacity is reached. It can be argued, from the single resource perspective, that if both the processing and storage demands are stretching working memory to its capacity limits, then combining the task elements should result in a substantial drop in accuracy as seen in the current experiment.

The findings of the current study are inconsistent with a multiple-component working memory system thought to offer online processing and temporary storage of information by means of a number of specialized cognitive functions (Baddeley, 1986; Baddeley & Logie, 1999). These theories predict that there will be no or only minimal trade-off between processing and storage due to the coordination of these disparate tasks rather than these tasks drawing on the same central processor. Cocchini et al. (2002) found minimal disruptions when two tasks were combined and concluded that a multiple component working memory model provided a better account of performance in concurrent immediate tasks than either models that assume a single capacity system for processing and storage or a limited capacity attentional system combined with active memory traces.

Similarly, Duff and Logie (2001) argued that storage and processing do not share a single capacity. Using a version of the sentence span task, they found that the phonological loop component of working memory managed the retention of the final word of each sentence while sentence processing was handled by the central executive. They argued that assuming the central executive coordinates combined task performance as well as dealing with processing, then the overall drop in performance on the two tasks can be attributed to an increase of load imposed on the executive by coordination. Contrary to these studies, the current study found a large difference (ranging between 18 and 40 percent) between the span and the perform conditions. Multiple capacity theories would predict smaller trade-offs than those seen in the current experiment as they would be due to the coordination of dual-task performance by a supervisory system such as the central executive (Baddeley & Hitch, 1974). Consequently, the magnitude of the trade-off between processing and storage seen in the current study is difficult to reconcile with multiple capacity theories.

The results of the current study established that there is indeed a trade-off between processing and storage and that this trade-off influences both accuracy of recall and response time within working memory tasks. Further, the current results suggest that performance costs are only present when a processing threshold has been reached. These findings support single capacity theories of working memory. The next section will examine the role of task difficulty and associated processing costs.

3.4.2 Processing Task Complexity Influences Recall Performance

Based on the findings of the pilot study the present study employed two combination of tasks. Hard spans which involved three different tasks: High/Low (magnitude judgments), Odd/Even (parity judgements) and Digit/Word (form judgments) tasks and easy spans which involved three form judgements: Digit/Word, Red/Green and Big/Small. Results from the pilot study revealed that RTs in both the High/Low and Odd/Even tasks were significantly slower than all of the other judgements. This was also supported by the single task condition of the present study. Based on this discrepancy in reaction time, it was predicted that the hard span task combination would lead to reduced accuracy when compared to the easy span task combination.

The results of the current study demonstrated that task difficulty influenced working memory capacity. Overall, accuracy was higher in the easy condition than the hard condition. This supports theories that propose a single cognitive resource is responsible for both processing and storage of information in working memory. The influence of task difficulty suggests span accuracy is reduced not only by the addition of a processing task but also the complexity of this task. Importantly, this demonstrates that as either working memory load and/or processing demands increase (i.e. due to a greater number of items held in memory or because of dual-task complexity), there is an increase in errors and response latencies (Anderson et al., 1996; Baddeley, 1986; Caplan et al., 1992).

Easy and hard spans in the current experiment allowed the manipulation of processing requirements and storage requirements independently. There are very few studies that have examined the role of complexity within a modality. Kemps (1999) examined the role of processing complexity in visual working memory. She suggested that task complexity was moderated by an interaction between difficulty and the amount of information presented. She concluded that complexity is an important characteristic of visuospatial working memory. Consistent with the current study these findings suggest that working memory capacity is determined not only by the amount of information held but also by the complexity of concurrent processing tasks. The influence of complexity of concurrent processing tasks on storage suggests that there is a single capacity system which is responsible for both these processes.

Several studies have suggested that it is not the overall cognitive demand of dual-task requirements which determines processing costs but the type of tasks combined. Cocchini et al. (2002) found there was a drop in accuracy when articulatory suppression was combined with a verbal memory task but not with the visual memory task. Cocchini et al. concluded that a multiple component working memory model provided a better account of performance than either models that assume a single capacity system for processing and storage or a limited capacity attentional system combined with active memory traces. In contrast, the current study found that processing requirements within the same modality (all tasks in the current experiment were verbally mediated) influenced overall capacity of working memory. While the current findings do not refute this postulation, they do suggest that it is not the only factor that influences the processing-storage relationship. Instead the current findings suggest that the amount of information held in working memory may also be reduced due to increased processing demands of the tasks within the learned sequence.

There are theories of working memory that have been defined in terms of limits of activation (Anderson et al., 1996; Caplan et al., 1992; Just et al., 1996), however such theories may not account for the processing complexity effect seen in the current study. Halford and colleagues (Halford et al., 1998) presented an alternative definition of working memory capacity that included processing complexity. They suggested that working memory is best defined as complexity of relations that can be performed in parallel. When processing capacity is defined in this way, the limiting factor is not merely the number of items or the amount of information, but the relations between entities.

Processing demand is the effect exerted by task complexity on a performer and it reflects the requisite cognitive resources. The core proposal of this theory is that demand is a function of relational complexity (Halford et al., 1998). That is, the more interacting variables to be processed in parallel, the higher the demand. The resources allocated to a task vary as a function of demand and performance. More resources must be allocated to higher demand tasks in order to maintain performance. The results of the current study demonstrate that increasing the complexity of relations between storage and difficulty of task performance, resulted in a significant reduction in performance. From this perspective, accuracy decreases as a function of both List-Length and task difficulty. For example, when individuals are required to recall only short sequences, central capacity limits have not been reached and therefore individuals allocate less resources to the task. This was seen in the current study; the List-Length 4 hard condition had higher accuracy than the List-Length 4 easy condition. The additional processing requirements of the List-Length 4 hard condition equated closely to optimum processing resulting in near perfect recall. Conversely, due to the reduced processing requirements in the List-Length 4 easy condition individuals may have allocated less attention to the task and this therefore resulted in reduced accuracy. While this effect seems counterintuitive, it has been reported in numerous experiments examining the relationship between attention and working memory (Lavie & de Fockert, 2005; Lavie et al., 2004).

In the List-Length 6 conditions, memory processing requirements were higher such that participants were required to recall a longer sequence of tasks. Here, additional processing requirements of the hard task interfered with the process that maintained sequences in an active state and therefore the opposite results were seen. Consequently, accuracy was reduced in the hard condition when compared to the easy condition. This distinction can be explained using the concept of relational complexity. Halford et al.'s (1998) theory provides a way of blending serial and parallel processes, with serial processing being necessitated by limitations in the complexity of structures that can be processed in parallel. For more complex representations, either the representation must be chunked into fewer components (with the result that some of the relational structure becomes temporarily inaccessible) or the task must be segmented into smaller components that are processed serially, or both. Thus, the need for serial processing strategies can be seen as a consequence of processing capacity limitations.

This theory implies that the traditional approach of defining limitations in terms of items is inappropriate for processing capacity (Halford et al., 1998). Instead, the limit should be defined by the number of independent components that need to be processed in parallel. The concept of a chunk is retained but is extended to include conceptual chunks, which represent compressed relational instances. In terms of the current findings, as the amount of information to be retained is increased (as seen in the List-Length 6 condition), processing limitations (i.e. the ability to process representations in parallel), become more apparent. When this occurs, additional processing requirements (i.e. the hard condition) extend beyond the processing capacity of the system which in turn reduces working memory capacity.

The distinction between easy and hard span tasks in the current study suggested that working memory capacity is influenced by the difficulty of the processing task in dual-task situations. This finding supports the notion that there is a single capacity that is involved in both storage and processing. This means that working memory capacity is determined not only by the amount of information held and the presence of an additional processing task, but also by the difficulty of the processing task. An alternative to the cognitive load view of processing and storage is the notion that working memory capacity should be defined by the number of operations that can be performed in parallel. This notion will be discussed in more detail in the general discussion.

3.4.3 Task-switching and Working Memory

The ability to switch flexibly between tasks allows people to adapt to changing demands in the environment. However, task-switching takes time and produces interference, as is evident in a variety of procedures that compare performance when tasks change, with performance when tasks remain constant (Allport, et al., 1994; Gopher et al., 2000; Logan & Bundesen, 2003; Rogers & Monsell, 1995). Several accounts of task-switching suggest that switch-costs are associated with changing set which can be explained by working memory processes (Baddeley et al., 2001; Mayer & Kliegl, 2003; Rubenstein et al., 2001). Alternatively, switching can also be seen as a process within working memory (Barrouillet et al., 2004; Cowan, 2005). Task-switching in the current experiment was determined by attempting to discriminate switch costs from both recall and performance of tasks. Switch costs were calculated by adding reaction times from the single task condition to the memory span task condition (referred to as the combined condition) and comparing it to reaction times from the perform task condition (as per Logan, 2004).

Based on Logan's (2004) findings, it was predicted that reaction times in the perform condition would be significantly slower than the combined condition. Furthermore, these additional reaction time costs would be attributed to task-switching. The results of the current study were not consistent with Logan's findings such that reaction times in the combined condition were significantly slower than the perform condition. This finding was the opposite of what was expected and indicate that there were no switch costs present between tasks.

The current results may have differed from Logan's (2004) due to the difference in the conceptualisation of switch costs between the two studies. Logan's combination of the single and span task was based on list position, for example, single task for position three in a sequence was combined with memory span in position three. Logan did not account for reaction time differences as a result of variations in task difficulty and in his work the single task conditions were equated in terms of list position. Conversely, the current study combined the reaction times from the memory span task and the single task based on the type of task being performed. Thus, although list position was taken into account in the span condition and perform condition, the single task condition was not added to the memory span condition based on list position. Instead, the single task reaction time was determined by the task completed and consisted of the mean reaction time for each participant performing the task as determined by the single task condition. This allowed the comparison of the span and perform conditions in a way that accounted for the differences in reaction time seen in the pilot study and single task condition. This alternative conceptualisation suggests that switch costs are not present when task difficulty is taken into account in the task-span procedure. This finding means that the current method of measuring switch costs (Logan, 2004) may require modification to specifically take into account difficulty of a task within a span.

In his theoretical paper, Monsell (2003) suggested that three factors were associated with task switch costs: task-set reconfiguration costs, transient task-set inertia, and associative retrieval. In the current study as with Logan (2004), participants were required to learn a sequence of tasks in the study phase and then recall or recall and use these tasks in a later test stage. Given that task sequence was presented to the participants prior to the presentation of the target stimulus and was not stimulus driven, it is likely that participants in the current study were aware of the upcoming task prior to the presentation of the target stimulus. Consequently, task switch costs, as defined by Logan (2004) may not have been captured in the current study using this methodology. This possibility will be discussed in more depth in Experiments 2 and 3.

Some researchers have suggested that working memory has an inherent role in task-switching, specifically, that task reconfiguration involves processes that operate in working memory. Changing the contents of working memory is sufficient to change performance (i.e. changing goals and changing stimulus-response mapping rules; Mayr & Kliegl, 2000; Rubinstein et al., 2001; Sohn & Anderson, 2001). Others argue that reconfiguration involves processes outside of working memory as well as processes that operate on working memory; merely changing goals is not sufficient. The subordinate processes must also be reprogrammed (Logan & Gordon, 2001; Meiran, 2000). Still others argue that switch costs only reflect long-term memory processes that are outside of working memory. Switch costs reflect interference from past task sets or past associations to the stimuli under different task sets (Allport et al., 1994; Allport & Wylie, 2000; Meiran, & Kessler, 2008). The findings of the current experiment support theories suggesting that task-switching, specifically task set reconfiguration involves processes that occur outside of working memory. This proposition will be considered more in the second experiment.

Overall, the results of Experiment 1 found little support for switch costs above and beyond the time required to perform the task. While Logan (2004) found that reaction times in the perform condition were slower than the combined condition, this was not supported by the current research. Instead, the present findings indicate that there is no relationship between task-switching and working memory. This may in part be due to a difference in conceptualisation of the combined condition in the current study and raises concerns about the validity of Logan’s methods for determining switch costs.

3.4.4 Summary and Conclusion

In summary, the results of Experiment 1 suggest that additional processing requirements through dual-task performance reduce storage capacity and that manipulating processing requirements using task difficulty also reduce recall of material. Collectively, these finding suggest that there is a central processing limit that is responsible for both processing and storage of information within working memory. Thus, as processing demands increase storage capacity is reduced.

The findings of the current experiment support theories that suggest task-switching, specifically task set reconfiguration, involves processes that occur outside of working memory. However, there are numerous methodological factors that may have influenced this result (i.e. the role of task difficulty). Experiment 2 will further examine the role of working memory on task-switching by alternating not only the sequence or List-Length (as done in the current experiment) but also the number of tasks that can be present within a sequence.

Experiment 2

4.1 Aims and Hypotheses

The role of grouping has been well established within the working memory literature (Bower, 1972; Cowan, 2001; Gobet et al., 2001; Miller, 1956). Organisational processes exert large effects on memory, both in remembering novel information over short intervals and in learning material over a longer term (Bower, 1972). The aim of Experiment 2 is to examine the role of chunking on working memory capacity and task-switching. This was done by manipulating not only the List-Length (as in Experiment 1) but also by the number of tasks to be recalled within that span. Thus, the current experiment altered the number of tasks to be remembered as a way of reducing the amount of possible chunking.

Based on previous research (Logan, 2004) it was predicted that there would be no difference between tasks that required only the recall of task sequences (memory span condition) and tasks that required both the recall and completion of tasks (perform condition).

Research suggests that increasing the amount of information held in working memory reduced the accuracy of recall (Miller, 1956). Thus, it was predicted that increasing the number of tasks to be remembered would result in reduced accuracy and slower reactions time across lists-lengths.

Further, given the predicted role of working memory in task-switching (Baddeley et al., 2001; Barrouillet, Bermedin & Camos, 2004; Cowan, 2005; Mayer & Kliegl, 2003; Rubenstein et al., 2001) it was predicted that increasing the number of tasks within a sequence would increase switch costs in terms of both reduced accuracy and increased reaction time.

As with the first experiment, based on the findings of Logan (2004), it was predicted that reaction times for the perform condition would be significantly slower than the combination of the single task and memory span condition and that these additional reaction time costs would be considered as the cost due to switching between tasks.

4.2 Method

4.2.1 Design

Experiment 2 employed a 3-way within-subjects repeated measures design. There were three independent variables; Task-Type (2 levels; memory span & perform), Number of Switches (3 levels; 3, 4 & 5), and List-Length (3 levels: 4, 6 & 8). The two dependent variables were reaction time and accuracy.

4.2.2 Stimuli and Apparatus

The stimuli and apparatus for Experiment 2 were identical to that in Experiment 1.

4.2.3 Procedure

Participants were seated as described in Chapter 2. At the beginning of each trial, the word 'Ready' was presented on the computer screen. Participants were required to press the space bar to begin the trial. As with Experiment 1, each list involved a study phase and a test phase. Each study list was preceded by a display which included the following statement: "Task List-Length *N*," where *N* ranged from 4 to 6. Each task name was presented for 1000ms and was followed by a 1000ms blank screen before the next task name was presented. Procedures were identical to those used for Experiment 1 except for the following alteration. In Experiment 2 there was no division between task difficulty easy and task difficulty hard. Further, unlike the first experiment where the number of tasks to be recalled in a sequence remained constant (three tasks per sequence), the number of potential tasks in Experiment 2 varied. Thus, in addition to List-Length changing (4, 6, or 8), the number of potential tasks involved in a sequence varied (3, 4, or 5). Once again, participants were advised to use the strategy of remembering only the first word of each task pair.

As with Experiment 1, participants were given three practice trials each for the span and perform conditions. List-Length 4 had either 3 or 4 switches for a total of 12 trials, the List-Length 6 condition had either 3, 4 or 5 switches for a total of 18 trials and finally the List-Length 8 condition had either 3, 4, 5 or 6 switches for a total of 24 trials. Consequently, there were 54 trials each for the span and the perform conditions. In Experiment 2, the total number of trials was 108.

4.3 Results

4.3.1 Accuracy

The proportion of trials in which participants achieved 100 percent accuracy was calculated for each participant as a function of number of switches (3, 4, or 5) and List-Length (4, 6, or 8) for both the memory span (Figure 7) and perform conditions (Figure 8). In Experiment 2 analysis was divided into two components. This was done to account for the fact that a List-Length of 4 could not accommodate 5 switches, thus separate analyses were conducted for List-Lengths 4, 6, and 8 across 3 and 4 switches and for List-Lengths 6 and 8 across 3, 4, and 5 switches.

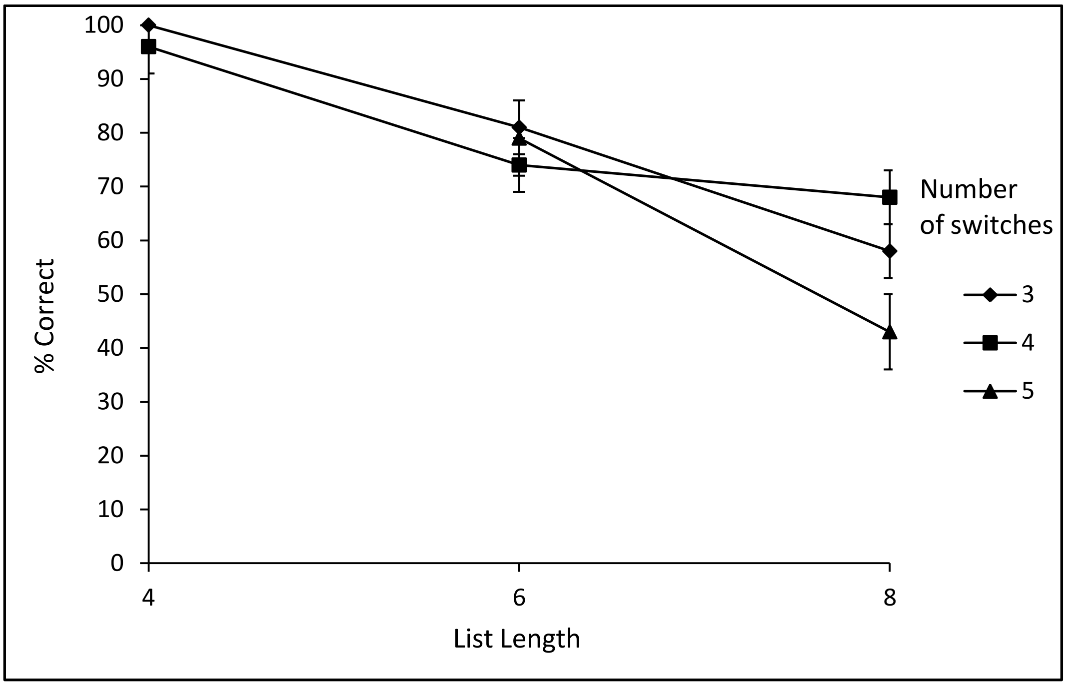

Figure 7. Proportion of 100 percent correct trials and standard error across the number of switches and List-Length for the memory span condition.

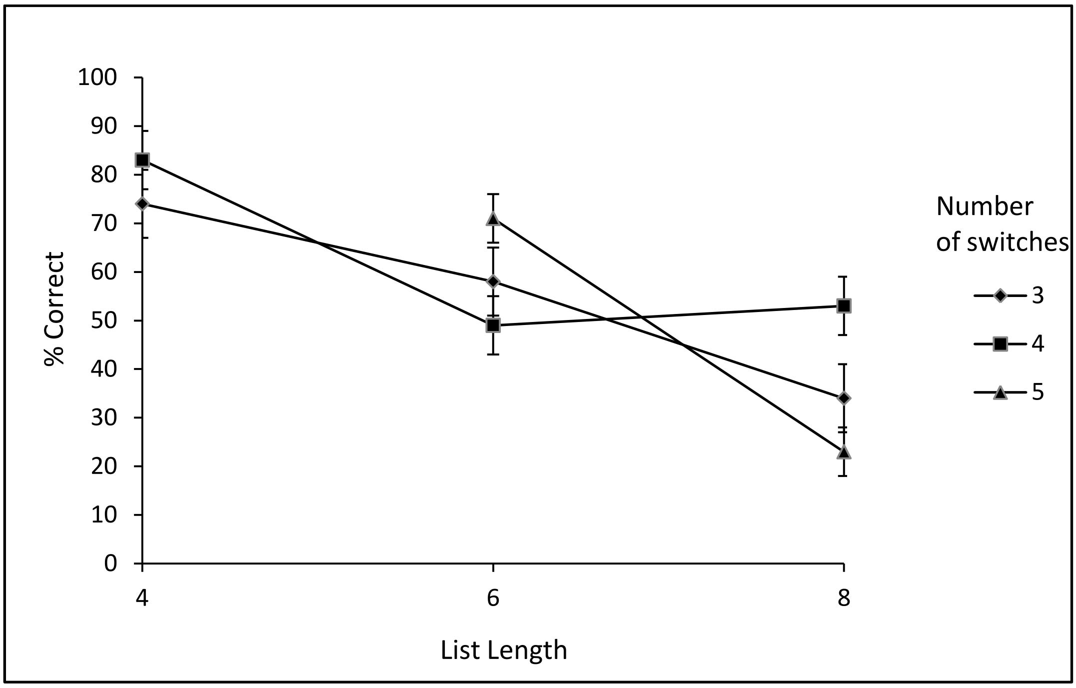

Figure 8. Proportion of 100 percent correct trials and standard error across the number of switches and List-Length for the perform condition.

A 2x3x2 and 2x2x3 repeated measures ANOVA were conducted for proportion of correct trials. Pairwise comparisons were conducted using Bonferroni corrections. Figure 7 shows the mean proportion of 100 percent accurate trials for the memory span condition as a function of number of switches and List-Length. Figure 8 shows the mean proportion of 100 percent accurate trials for the perform condition as a function of number of switches and List-Length.

When List-Lengths 4, 6, and 8 were compared across 3 and 4 switches, there was a significant main effect for task type on proportion of trials 100 percent correct, $F_{(1,15)}=52.55$, $p<.01$, such that accuracy in the memory span condition was significantly greater than in perform condition.

As expected there was a significant main effect for List-Length, $F_{(1,15)} = 22.31$, $p < .01$, such that the accuracy for List-Length 4 was significantly greater than both List-Length 6 and List-Length 8. Further, accuracy for List-Length 6 was significantly greater than that of List-Length 8.

When comparing List-Lengths 6 and 8 across 3, 4, and 5 switches, again there was a significant main effect for task type on proportion of trials 100 percent correct, $F_{(1,15)} = 70.22$, $p < .01$ such that accuracy in the memory span condition was significantly greater than in the perform condition.

As expected there was a significant main effect for List-Length, $F_{(1,15)} = 31.33$, $p < .01$ such that the accuracy for List-Length 6 was significantly greater than List-Length 8. There was no main effect for the number of switches.

There was also a significant interaction between List-Length and number of switches, $F_{(1,15)} = 14.60$, $p < .01$. Pairwise comparisons revealed that accuracy was significantly higher for the List-Length 6, 5 switches condition ($M = .75$, $SE = .06$) than for the List-Length 6, 4 switches condition ($M = .61$, $SE = .07$ $t_{(15)} = -2.71$, $p < .05$). Further comparisons revealed that accuracy was significantly greater for List-Length 8, 3 switches condition ($M = .46$, $SE = .07$) than for the List-Length 8, 5 switches condition ($M = .33$, $SE = .05$ $t_{(15)} = 2.25$, $p < .05$) and that accuracy was significantly greater for List-Length 8, 4 switches condition ($M = .60$, $SE = .05$) than for the List-Length 8, 5 switches condition ($M = .33$, $SE = .05$, $t_{(15)} = 6.35$, $p < .001$).

Overall, the accuracy data suggest that when additional processing of information is required there is a reduction in accuracy. Somewhat predictably, the results also suggest that as the number of items to be recalled increased, accuracy decreased. Finally, the results of Experiment 2 suggest that the relationship between number of task and List-Length in terms of accuracy, was not linear. Accuracy did not reduce simply as the number of tasks within a sequence increased, instead there was a complex relationship between the number of tasks to be recalled within a sequence and List-Length.

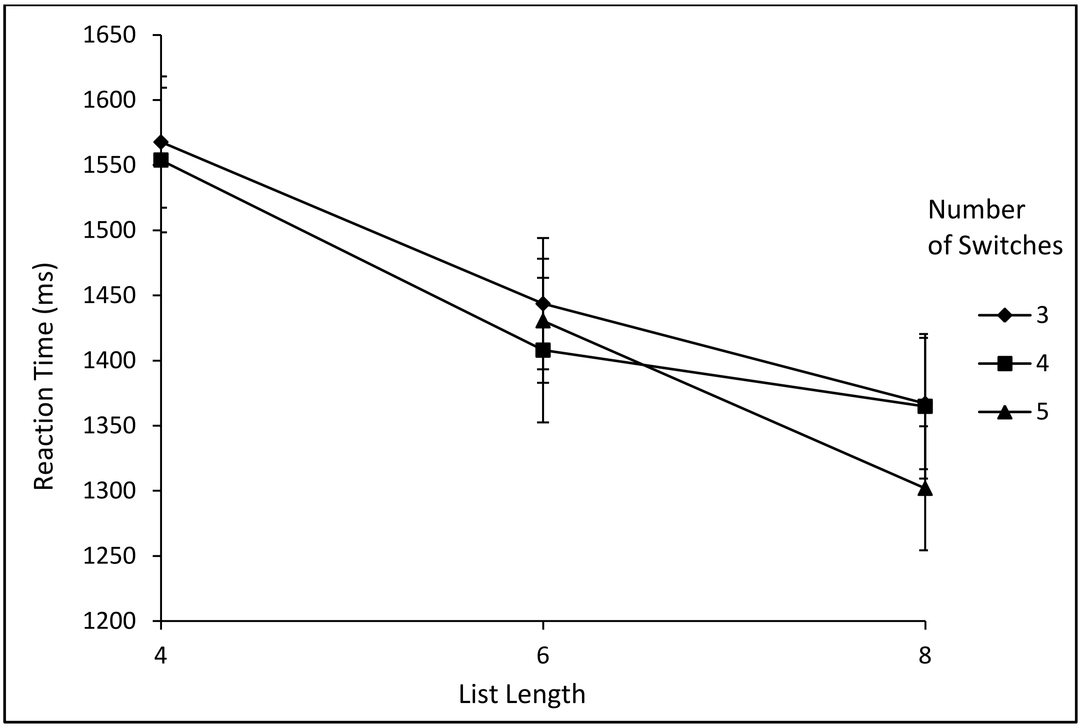

Figure 9. Mean reaction times (ms) and standard error across the number of switches and List-Length for the memory span condition.

4.3.2 Reaction Time

The mean reaction time of trials in which participants achieved 100 percent accuracy was calculated for each participant as a function of number of switches (3, 4, or 5) and List-Length (4, 6, or 8) for both the memory span (Figure 9) and perform

(Figure 10) conditions. As with the accuracy analyses reported earlier, analysis was divided into two components. Thus, separate analyses were conducted for List-Lengths 4, 6, and 8 across 3 and 4 switches and for List-Lengths 6 and 8 across 3, 4, and 5 switches. A 2x3x2 and 2x2x3 repeated measures ANOVA were conducted for mean reaction time of correct trials. Pairwise comparisons were conducted using Bonferroni corrections.

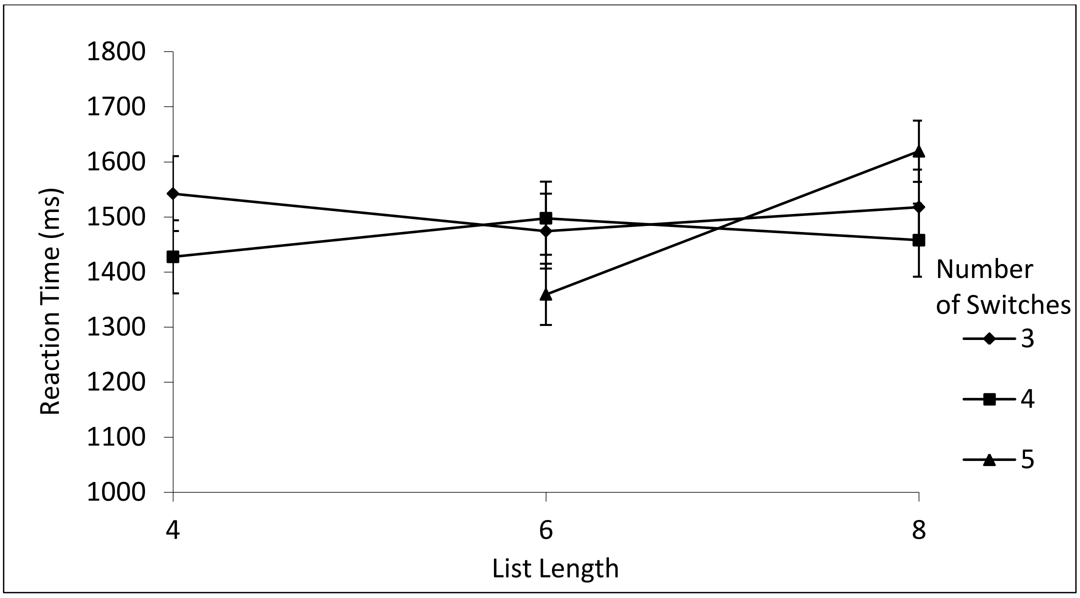

Figure 10. Mean reaction times (ms) and standard error across the number of switches and List-Length for the perform condition.

When comparing List-Lengths 4, 6, and 8 across 3 and 4 switches, there was a significant main effect for task type on mean reaction time, $F_{(1,15)}=6.61$, $p<.05$ such that mean reaction times in the memory span condition were significantly faster than in perform condition.

Further, there was a significant main effect for the number of switches, $F_{(1,15)}=7.67$, $p<.05$ such that lists with 4 switches produced significantly faster RTs than lists with 3 switches. There was no significant main effect for List-Length.

There was also a significant interaction between task type and List-Length, $F_{(1,15)}$=10.08, $p<.01$. Pairwise comparisons revealed that RTs in the List-Length 6 span condition (M=1425.79, SE=45.80) were significantly faster than the List-Length 6 perform condition (M=1596.56, SE=64.45, $t_{(15)}$= -2.36, $p<.05$). The RTs List-Length 8 span condition (M= 1365.90, SE=51.62) were similarly significantly faster than the List-Length 8 perform condition (M=1587.56, SE=62.23, $t_{(15)}$= -3.31, $p<.01$).

When comparing List-Lengths 6 and 8 across 3, 4, and 5 switches again there was a significant main effect for task type on mean reaction time, F $_{(1,15)}$=21.55, $p<.01$ such that mean reaction times in the memory span condition was significantly faster than in the perform condition. There was no significant main effect for List-Length or number of switches.

In addition, there was a significant interaction between task type and List-Length, $F_{(1,15)}$=7.84, $p<.01$. Pairwise comparisons revealed that the RTs in List-Length 8 span condition (M= 1359.86, SE=53.38) were significantly faster than the List-Length 8 perform condition (M=1618.39, SE=52.34, $t_{(15)}$= -4.18, $p<.001$).

There was a 3-way interaction between task type, number of switches and List-Length, F $_{(1,15)}$=10.39, $p<.01$. Two two-way ANOVAs were conducted to examine this interaction, one examining the span condition and the other examining the perform condition. The two-way ANOVA, for the span condition revealed a significant main effect for List-Length $F_{(1,15)}$=6.46, $p<.05$, such that reaction times were significantly faster for List-Length 8 as compared to List-Length 6. There was no significant main effect for number of switches, nor was there a significant interaction. The two-way ANOVA for the perform condition found a trend for the influence of List-Length on reaction time ($p=.053$). There was no significant main effect for number of switches, however there was a trend in the interaction between List-Length and number of switches ($p=.06$).

4.3.3 Reaction Time Measure of Task-Switching

Further comparisons to examine the role of switch costs were conducted using Logan's (2004) additive method; an individual's single task RT was added to their span task RT and then compared to the perform RT to examine whether there were additional costs associated with switch costs beyond those of task performance. The mean reaction time of trials in which participants achieved 100 percent accuracy was calculated for each participant as a function of number of switches (3, 4, or 5) and List-Length (4, 6, or 8) for both the combined (Figure 11) and perform (Figure 12) conditions. As with the accuracy analyses reported earlier, analysis was divided into two components. Thus, separate analyses were conducted for List-Lengths 4, 6, and 8 across 3 and 4 switches and for List-Lengths 6 and 8 across 3, 4, and 5 switches.

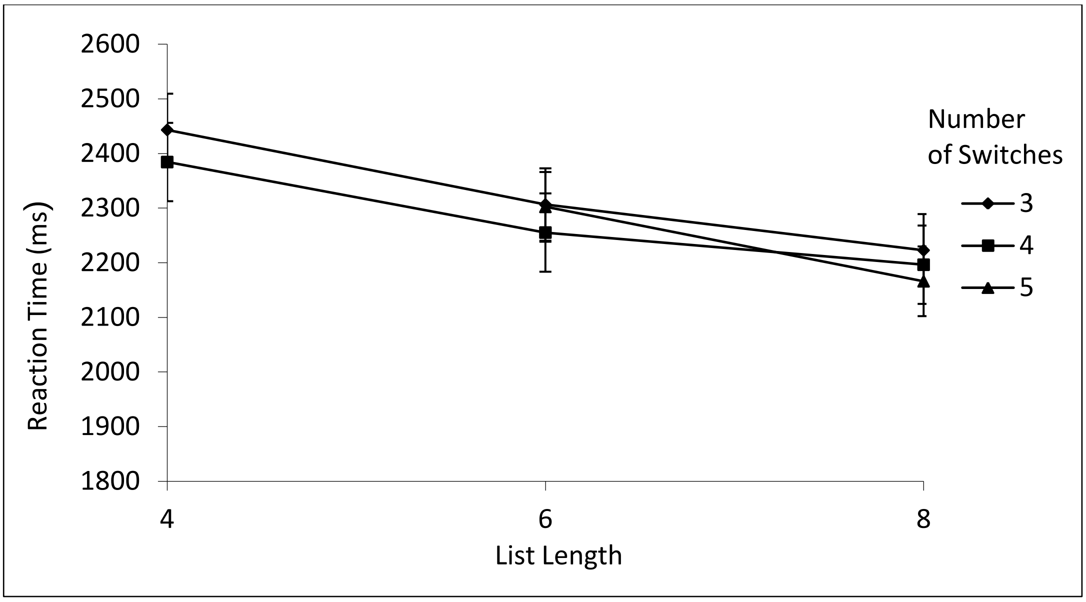

Figure 11. Mean reaction times (ms) and standard error across the number of switches and List-Length for the combined condition.

A 2x3x2 and 2x2x3 repeated measures ANOVA were conducted for mean reaction time of correct trials. Pairwise comparisons were conducted using Bonferroni corrections. When comparing List-Lengths 4, 6, and 8 across 3 and 4 switches, there was a significant main effect for task type on mean reaction time, $F_{(1,10)}=135.74$, $p<.01$ such that mean reaction times in the combined condition were significantly slower than in perform condition.

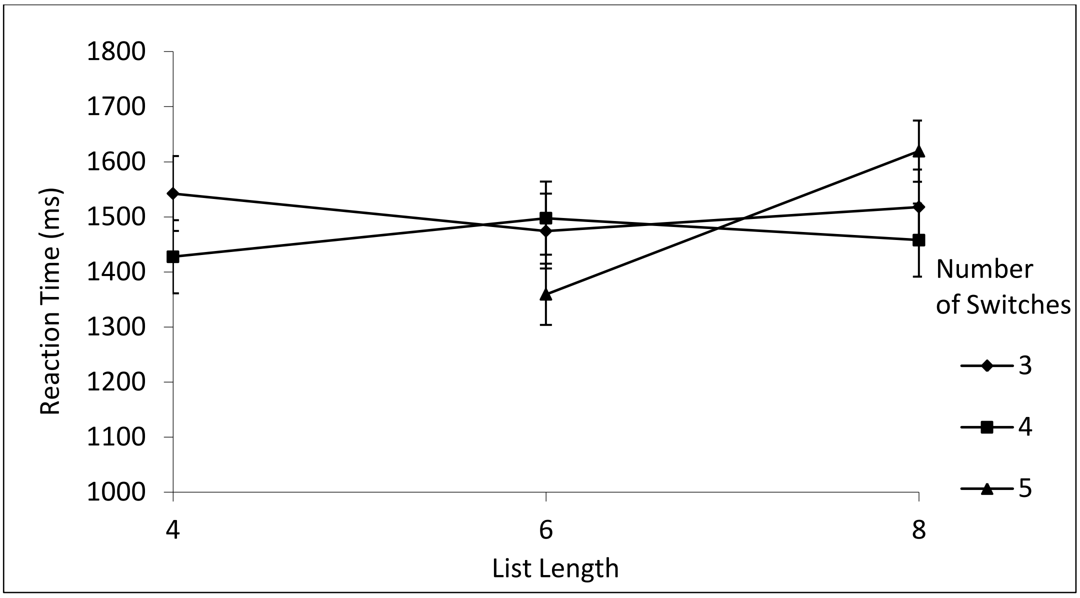

Figure 12. Mean reaction times (ms) and standard error across the number of switches and List-Length for the perform condition.

Further, there was a significant main effect for the number of switches, $F_{(1,10)}$ =7.80, $p<.05$ such that RTs in lists with 4 switches were significantly faster than lists with 3 switches. There was no significant main effect for List-Length.

There was also a significant interaction between task type and List-Length, $F_{(1,10)}$=23.39, $p<.01$. Pairwise comparisons revealed that RTs in the List-Length 4 combined condition (M=2507.12, SE=74.22) were significantly slower than the List-Length 4 perform condition (M=1529.23, SE=66.56, $t_{(14)}$= -15.24, $p<.001$). Further, pairwise comparisons revealed that RTs in the List-Length 6 combined condition (M=2375.65, SE=62.77) were significantly slower than the List-Length 6 perform condition (M=1596.56, SE=64.45, $t_{(14)}$= -10.45, $p<.001$) and that RTs in the List-Length 8 combined condition (M= 2317.72, SE=66.08) were significantly slower than the List-Length 8 perform condition (M=1587.56, SE=62.23, $t_{(15)}$= -10.49, $p<.001$).

When comparing List-Lengths 6 and 8 across 3, 4, and 5, switches again there was a significant main effect for task type on mean reaction time, $F_{(1,8)}=233.68$, $p<.001$ such that mean reaction times in the combined condition were significantly slower than in the perform condition. There was no significant main effect for List-Length or number of switches.

There was a significant interaction between task type and List-Length, $F_{(1,8)}=7.46$, $p<.05$. Pairwise comparisons revealed that RTs in the List-Length 6 combined condition (M= 2377.08, SE=53.38) were significantly slower than the List-Length 6 perform condition (M=1618.39, SE=52.34, $t_{(14)}=-11.94$, $p<.001$) and that RTs in the List-Length 8 combined condition (M= 2312.06, SE=68.32) were significantly slower than the List-Length 8 perform condition (M=1618.40, SE=52.34, $t_{(14)}=-10.18$, $p<.001$).

There was a 3-way interaction between task type, number of switches and List-Length, $F_{(1,15)}=6.79$, $p<.05$. Two two-way ANOVAs were conducted to examine this interaction, one examining the combined condition and the other examining the perform condition. The two-way ANOVA for the combined condition revealed a significant main effect for List-Length $F_{(1,15)}=5.98$, $p<.05$, such that reaction times were significantly faster for list- length 8 versus List-Length 6. There was no significant main effect for number of switches, nor was there a significant interaction. The two-way ANOVA for the perform condition found that there was a trend for List-Length on reaction time (p=.053) and a trend for the interaction between List-Length and number of switches (p=.06).

Overall, RT data was less clear than accuracy data. Participants were faster in the span condition than the perform condition. Reaction time was not related to the number of items within a sequence nor was reaction time related to List-Length. As within Experiment 1, the additive method of Logan (2004) did not yield switch costs in the perform condition above and beyond the additional requirement of task performance. Indeed, RTs in the perform condition were faster than the combination of the single task and memory span condition.

4.4 Discussion

The aim of the second experiment was to examine the nature of capacity limitations in relation to both chunking and task switch load. As with the first experiment the second experiment used the task-span procedure, developed by Logan (2004) with some modifications. The major modification in Experiment 2 was to adjust the number of items that could be presented in the to-be-remembered sequence during the study phase. In Experiment 1, participants were presented a sequence of 4, 6, or 8 tasks and each sequence consisted of three task types; High/Low, Odd/Even and Digit/Word, or Digit/Word, Red/Green and Big/Small. Thus, regardless of List-Length only three tasks needed to be used at any one time. In the second experiment, participants were again presented with sequences of 4, 6, or 8 tasks. However, this sequence could be any combination of the five tasks (High/Low, Odd/Even, Digit/Word, Red/Green, Big/Small) and the number of tasks used in a sequence was either 3, 4, or 5. This additional requirement aimed to manipulate the working memory component of the task-span procedure while holding the number of switches constant. For example, in the List-Length 6 condition, there were 5 switches within a sequence but the number of task types varied (3, 4, or 5 tasks). Consequently, more task rules had to be held active and recalled during processing.

4.4.1 The Processing Storage Trade-Off

Based on previous research, it was predicted that there would be no significant difference between tasks that required only the recall of task sequences (memory span condition) and tasks that required both the recall and completion of tasks (perform condition). The results of Experiment 2 support those of Experiment 1 and suggest that accuracy was greater when participants were only required to recall the task (task-span condition) as compared to when they were required to both recall and complete the task (the perform condition). These results were inconsistent with Logan (2004; Experiment 1) who found that accuracy in the memory span and perform condition were essentially equivalent. However, these findings support those of Experiment 1 (current study) and suggest that additional processing requirements consistently resulted in a reduction in accuracy of sequences recalled regardless of varying degrees of difficulty or number of tasks to be recalled. Experiment 2 found that there was a large difference (ranging between 8 and 26 percent with a mean difference of 19 percent) between the span and the perform conditions. Thus, as with Experiment 1 the results of Experiment 2 are consistent with theories which propose that a single capacity is responsible for both processing and storage.

4.4.2 Chunking is Mediated by Both Sequence Length and Number of Tasks to be Remembered.

Based on previous research (Cowan, 1988; 2001; Miller, 1956), it was predicted that increasing the number of tasks to be remembered would result in reduced accuracy across List-Length sequences. The current study found that the relationship between the number of tasks to be recalled within a sequence and accuracy was not simply linear in nature. The results of Experiment 2 revealed a significant interaction between the number of switches and List-Length when comparing 3, 4, and 5 switches across List-Lengths 6 and 8. The pattern of these results however was somewhat surprising. Accuracy was significantly higher in the List-Length 6 when there were 5 switches compared to 4 switches. Further, accuracy was higher for List-Length 8 when there were 3 switches than when there were 5 switches. These results seem difficult to reconcile with the simple assumption that increasing the number of switches increases the working memory load of a particular task.

The results of the current study suggest that particular groupings may result in variations in performance as stipulated in previous research (Mclean & Gregg, 1967; Ryan, 1969; Wickelgren, 1964; 1967; 1970). Performance is not based on working memory load alone, in terms of sequence length or number of tasks within a sequence, but the grouping that occurs within a sequence. It can be argued that after a series of tasks is presented once, a ‘perceptual set’ is formed. A ‘perceptual set’ is defined here as a subconscious grouping of tasks to aid recall. Tasks outside this completed perceptual set may cause interference and result in a reduction in accuracy. Thus, the List-Length 6, 5 switches condition had higher accuracy than 4 switches. The List-Length 6, 5 switches condition contained one complete perceptual set (5 switches) and one additional task, thus the task grouping was 5+1. In the List-Length 6, 4 switches condition a List-Length of 6 contained one perceptual set (in this case 4 switches) and two additional tasks. Similarly, greater accuracy was seen in the List-Length 8 condition when there were 3 switches compared to 5 switches. This is because there were two complete perceptual sets and two additional tasks to be remembered in the 3 switches condition as compared to one complete perceptual set with an additional 4 tasks to be remembered in the 5 switches condition. The List-Length 8, 4 switches condition was also more accurate than List-Length 8, 5 switches condition. Here List-Length 8, 4 switches, contained two complete perceptual sets with no additional tasks, while the List-Length 8, 5 switches contained one perceptual set with an additional 3 tasks to be remembered. Additional tasks may act as interference and cause confusion and recall of these tasks may indeed be more difficult given that an individual must determine which tasks have been repeated in each sequence. From this perspective, remembering one repeated task is easier than remembering two repeated tasks.

The variation in grouping seen in the current experiment can be attributed to a hierarchical control structure. From this perspective, grouping is transient and depends on the nature of the task presented and chunk length varies on the basis of strategic and perceptual processes. This concept of hierarchical control is consistent with the early work of Wicklegren (1967; 1970) who examined rehearsal grouping and hierarchical organisation in short-term memory and found both item-to-item and serial position-to-item associations were involved in short-term memory. Further, he suggested that only two or three serial position cues were used, but that these serial position cues are hierarchically organised into a beginning, middle, and end, and have a beginning, middle, and end position within each grouping.

The current findings are also consistent with the work of Ryan (1969). In her second experiment she examined the role of irregular patterns of grouping on short-term recall. Participants were presented with sequences of nine digits that were divided into three groups. The number of groups per sequence never varied but the number within each group did. Temporal grouping was induced by introducing pauses to delineate groups. She found that participants recalled fewer items when there was an irregular pattern of grouping than when there was a regular pattern. She concluded that the effectiveness of temporal grouping in improving recall varies with the pattern of grouping. She suggested that irregularly distributed patterns are not as accurate as regular patterns because equally distributed pauses may lie in the improvement of coding of order information. In the discrimination of position along a continuum, it would be generally advantageous if the continuum could be divided by perceptual anchors. The current experiment extends these findings to suggest that regular chunking patterns are not limited to temporal groupings but also extend to perceptual groupings. For example, the List-Length 8, 4 switches condition had higher accuracy as there was regularity to the grouping; there were two complete sets or perceptual groups of four items within each List-Length of 8. In contrast, in the List-Length 8, 5 switches condition, there was no regularity to the group; there was one complete perceptual set of 5 items and 3 additional within each List-Length of 8. Accuracy of recall was reduced in this irregular grouping condition. This lends further support to the concept that chunking is hierarchically organised and determined by a combination of top-down and bottom-up processes.

More recently, Gobet et al. (2001) suggested that there are two types of chunks, conscious (top-down) goal oriented chunking and a second more automatic and continuous process of chunking during perception (bottom-up) known as perceptual chunking. Perceptual chunking is seen when primitive stimuli are grouped into larger conceptual groups such as the manner by which letters are grouped into words or sentences. The results of the current study suggest that top-down, goal oriented, and bottom-up perceptual chunking may occur together in unison. Goal-oriented chunking may occur at the sequence level whereby participants group tasks together into chunks. This is temporally determined and thus the first three tasks may be grouped with the next three etc. However, the current findings suggest that chunking may also occur at a more subconscious, perceptual level. From this perspective participants group tasks together to form perceptual sets as described earlier and tasks outside this perceptual set may in fact interfere with recall. Indeed, the results of the current study suggest that the manner in which chunks are constructed affects the types of generalisations made and also predicts typical errors or successes.

Perceptual task sets may be seen as long-term memory representations while List-Length may represent more of an attentional or working memory component. Research suggests that information in long-term memory can influence recall (Chen & Cowan, 2005). Long-term memory in the current experiment is invoked by the representation of each individual task within a sequence. Given that each task was practiced earlier in the experiment (single-task condition) and then subsequent use of these tasks in Experiment 1, it is likely that task representations were stored within long-term memory.

Additional tasks to the perceptual task sets may indeed result in interference with recall. Some theorists have argued that capacity of working memory span tasks that assess working memory are complex and often multiply determined (Lustig et al., 2001). Working memory span tasks have multiple study and test trials and participants are therefore required to manage both recall of upcoming trials and interference from previously presented trials, thus stopping interference at the time of recall (May et al., 1999). From this perspective the incomplete sets present interference; the larger the incomplete set, the more tasks that interfere with recall. Lustig et al. (2001) found that processes that underlie interference are critical in determining span scores. They termed this proactive interference.

Some theorists (Gobet, 2000) have suggested that when chunks recur during practice and study, they may evolve into more complex data structures such as templates; this allows information to be rapidly recorded into slots within that template. Templates offer both core information that cannot be changed and slots that allow the rapid updating of information. From the perspective of the current study, it can be argued that a template was created when numerous tasks were presented; however the template was not based on well learned associations between tasks but acted as a limiter within the entire series of five tasks. The slots were rapidly filled with tasks within each perceptual set. Additional tasks that did not fit within the template interfered with recall. Thus, a combination of the use of templates and interference of tasks outside of the template determines the amount of information recalled.

As with Experiment 1, the results of the current study can be viewed from the perspective of relational complexity. Halford and colleagues (Halford et al., 1998) suggested that working memory capacity is not determined by the number of items that need to be recalled but by the terms of the complexity of relations that can be processed in parallel. They argued that processing load is determined by the number of interacting components. Thus, there are a number of interacting variables that must be represented in parallel to perform the most complex process involved in the task using the least demanding strategy. The findings of the current study suggest that a combination of top-down and bottom-up processes are involved in recall. Temporal templates determined in long term-memory may assist at a perceptual level and this, combined with the strategy of chunking, may together maximise performance. As discussed earlier, the templates may act as an inhibitory mechanism to reduce interference which reduces overall processing complexity of the task. In the current experiment, accuracy was higher when there were fewer items outside the perceptual set which reduced interference (i.e. greater accuracy was seen in the List-Length 6, 5 switches condition compared to the List-Length 6, 4 switches condition).

The results of Experiment 2 suggest that there are both strategic (top-down) and perceptual processes (bottom up) acting in unison on the storage of information. Perceptual processes may be a result of templates being formed within long term memory. These slots are rapidly filled with tasks within each perceptual set. Additional tasks that do not fit within the template interfere with recall. Thus, it is a combination of the use of templates and interference of tasks outside of the template that determines the amount of information accurately recalled.

4.4.3 The Role of Working Memory Load on Task-switching

One of the aims of the second experiment was to see whether changing the number of tasks to be recalled would influence task performance. Specifically, whether increasing the number of tasks to be recalled would have an impact on switching efficiency. Based on the findings of Logan (2004), it was predicted that reaction times for the perform condition would be significantly slower than the combination of the single task and memory span condition and that these additional reaction time costs would be considered as the cost from switching between tasks. Consistent with Experiment 1 this hypothesis was not supported. Collectively, the current experiments indicate that when the single-task and the span conditions were combined, reaction times in the combined condition were significantly slower than the perform condition.

Task-switching load appeared to have little effect on reaction time performance or accuracy. Indeed, the only result was that 3 switches were found to be slower than 4 switches when comparing across List-Lengths 4, 6, and 8. Whilst these results seem counterintuitive, they may be explained by distinguishing between task-switching costs and task-mixing costs (Kray & Lindberger, 2000; Los, 1996; Meiran et al., 2000; Rubin & Meiran, 2005). The concept of task mixing costs was initially devised as a criticism of the historical conceptualizations of task-switching that compared single task blocks to mixed task blocks. It was suggested that this paradigm was confounded by other variables that differentiate these two block types, specifically the additional working memory requisites of more than a single set of task instructions and the division of attention between tasks (Rubin & Merian, 2005). Rubin and Merian (2005) examined task-mixing costs associated with task repetition within blocks of mixed tasks relative to task repetitions within blocks of single tasks. They tried to further dissociate between storage (which is affected by the number of sets) and manipulation (which is primarily influenced by task ambiguity). They found mixing costs only occurred with ambiguous stimuli and not with unambiguous stimuli (that only used one task) as mixed-task trials require the resolution of task ambiguity. Further, they found that holding multiple tasks in working memory did not add to task mixing costs.

The results of the current experiment are consistent with the findings of Rubin and Meiran (2005). Reaction time performance when comparing 3 switches to 4 switches may reflect task mixing costs rather than task-switching costs. It could be argued that if an additional switch load was involved in task performance in the perform condition, then additional tasks would lead to additional reaction time costs. Thus, it would be expected that reaction times would be greater in the 4 switches condition compared to the 3 switches condition. However, if interference was caused due to task mixing costs (as seen in the present study) then the 3 tasks may produce greater interference versus 4 tasks within a sequence of 4, 6, or 8. Returning to the concept of perceptual sets discussed earlier, tasks that fall outside of these perceptual sets cause interference and this interference or ambiguity may explain this result. Thus, as with the work of Rubin and Meiran (2005), competition between tasks during selection is a critical factor in controlling task sets and therefore may contribute to mixing costs.

The results of Experiment 2 suggest that increasing the number of switches within a sequence has little impact on the recall of information from working memory. The current findings are inconsistent with the suggestion that switch costs are elicited by task-set reconfiguration: a process mediated by working memory (Baddeley et al., 2001; Mayr & Kliegl, 2000; 2003). From this perspective, it would be expected that as the number of switches increase, the total time involved in task set reconfiguration also increases (Liefooghe et al., 2008). This was not seen in the current experiment. Liefooghe et al. (2008) showed that task-switching impaired working memory maintenance, however the size of the switch cost remained unaffected by the amount of information that was maintained. They argued that when task-switching calls upon working memory resources to a great enough extent, the concurrent maintenance of items in working memory is impaired. Further, they suggested that the impairment observed is a function of the additional amount of time task-switching occupies attention compared with task repetition. Thus, the amount of time that attention could be devoted to the refreshment of decaying memory traces was shorter during switches than repetition which resulted in greater deterioration in working memory. The current study found that increasing the number of task switches did not diminish working memory performance. Further, there was no evidence of reaction time being influenced by task switch load. The current finding challenges the proposal that task-switching sets are maintained in working memory itself (Logan & Gordan, 2001; Mayr & Kliegl, 2000; 2003) and it is consistent with the idea that some task elements, such as response codes are represented within long-term memory (e.g. Meiran & Kessler, 2008).

The current experiment differed from the work of Liefooghe et al. (2008) in a number of crucial ways. Firstly, the task was constructed in a different manner such that the working memory task was embedded within the processing task. Thus, the perform condition was innately dependent on the recall of task name in sequence from working memory. In other studies, researchers have used two parallel tasks with differing stimuli (Mayr, 2002; Mayr & Keel, 2000; Rubin & Meiran, 2005; Wylie & Allport, 2000), thus the focus of the task-span procedure (Logan, 2004) is on working memory and not on task-switching. There are considerably more tasks to remember in the task-span procedure, which is not typical of task-switching tasks. The recall of these tasks may be related to the different chunking patterns (as discussed in the previous section) and this may be masking switch costs. Finally, the current task used a dual-task methodology which actively required participants to alternate between storage and processing. If the distinction between the span and the perform condition is seen as constituting switch costs, then it could be argued that the results of the current study are consistent with Liefooghe et al. This final point will be discussed in more detail in Experiment 3.

The results of Experiment 2 do not rule out the possibility that the task switch occurs prior to the presentation of the target stimuli in the perform condition. Given that each trial consists of a study and test phase and that each participant is aware of the upcoming task prior to the presentation of the target, it is possible that advance preparation occurs prior to the presentation of the target stimuli and this mitigates any switch costs. For example, Meiran (1996) suggested that a time and effort consuming process that operates after a task shift precedes task execution, and presumably reflects the advance reconfiguration of processing mode. Similarly, Yeung & Monsell (2003) found that task-set preparation reduces that effect on task-set inertia.

Overall, the results of Experiment 1 and 2 have not provided support for the presence of task switch costs in the perform condition above and beyond the additional cost of processing. One reason for this may be advance preparation which may occur in the interstimulus interval before the presentation of the target stimuli. Given foreknowledge of an upcoming task, individuals often prepare ahead of time so that their performance on a subsequent task is faster. The more time invested in advanced preparation, the faster and less error prone the resulting performance (Altmann, 2004). Meiran (1996) found that task switch costs were almost entirely eliminated when participants were given sufficient time to prepare for the task-shift. He argued that task-switching is associated with a process that operated prior to task execution; this advanced preparation was consistent with the notion of advanced reconfiguration and the idea of cognitive control. In the current study, there was a distinction between the study and test phase. Given that this allowed participants to know about upcoming tasks prior to target presentation, it could be argued that it also allowed participants to prepare. Experiment 3 aimed to remove the influence of advance reconfiguration by introducing task cues that were presented simultaneously with the target stimuli.

4.4.4 Conclusion

Overall, the results of Experiment 2 supported the results of Experiment 1 and suggested that there is indeed a trade-off between processing and storage. This is consistent with theories suggesting a single capacity system that is responsible for both processing and storage of information in working memory. In addition, the results of Experiment 2 suggested that there are both strategic and perceptual processes acting in unison on the storage of information. Perceptual processes may be a result of templates being formed within long term memory and additional tasks that do not fit within the template interfere with recall. Thus, it is a combination of the use of templates and interference of tasks outside of the template that determines the amount of information recalled. Finally, the results of Experiment 2 did not provide support for the presence of task switch costs in the perform condition above and beyond the additional cost of processing.

Experiment 3

5.1 Aims and Hypotheses

Preparation can be interpreted as activating a set of mental structures in anticipation of upcoming task requirements (Altmann, 2004; Mayer & Kiegl, 2001). Here expectancy effect can play a part, that is, an individual has the opportunity to prepare for what is coming next. Thus, within the context of the task-span procedure, knowing which task is coming next may actively reduce switch costs. Three components are required to perform the task-span procedure accurately: (a) retrieving the task name that is appropriate for the current stimulus, (b) engaging the task set appropriate to the task name, and (c) performing the appropriate task on the target stimulus. Tasks can only be performed correctly if each of these steps is executed correctly. Logan (2004) suggested that the time to perform each task (RT) is the sum of the times required to execute each of these steps. Further, that RT provides insight into recalling task names, the executive processes involved in task-switching, and the subordinate processes involved in performing the tasks. However, when a task list is provided prior to testing, as in the task-span procedure, the opportunity exists to make the switch prior to the presentation of the stimuli. From this perspective, the majority of the retrieval and task-switch components occur prior to the presentation of the stimuli, thus reaction time only truly reflects the time taken to make a judgement not the time required to retrieve the task name or reconfigure the cognitive system to switch between tasks. The retrieval and switch components of the task are processed in the inter-stimulus interval between the presentation of two stimuli.

The aim of Experiment 3 was threefold: first, to examine the role of working memory load on the time taken to flexibly switch between tasks; second to develop an improved measure of the reaction time costs associated with task-switching and finally to reduce the influence of chunking by creating symbol-task pairs that constituted chunks in themselves. Experiment 3 used a modified version of the task-span procedure. In the modified task-span procedure, participants were no longer required to remember a sequential list of tasks, rather, they were required to remember a list of task types. Individuals were presented with a list of symbol-task pairs. In the study phase, individuals were given a list of potential switches and each potential switch had a different symbol assigned to it (e.g. a parity judgement paired with a triangle, △=ODD/EVEN). In the test phase, the symbol representing the type of judgement to be made was presented either alone (memory span condition) or with the target number/word (perform condition).

Based on the results of Experiment 1 and 2 that showed that there is a trade-off between processing and storage, it was predicted that accuracy would be significantly greater in the span condition than the perform condition.

Experiment 3 used symbol-task associations that allowed the formation of independent chunks. This attempted to reduce the effect of inter-item chunking within a sequence by increasing the complexity of the material to be remembered. This allowed the examination of Cowan's (1999) hypothesis that approximately 4 chunks can be held in working memory at any time.

As with Experiment 2, Experiment 3 aimed to explore the relationship between working memory and task-switching. In Experiment 2, the influence of working memory load on switch costs may have been mediated by inter-item chunking. The addition of task-shape associations aimed to curb the influence of inter-item chunking and given the predicted role of working memory in task-switching (Baddeley et al., 2001; Barrouillet et al., 2004; Cowan, 2005; Mayer & Kliegl, 2003; Rubenstein et al., 2001), it was predicted that increasing the number of tasks within a sequence would increase switch costs in terms of both reduced accuracy and increased reaction time.

Cued recall allows for a more accurate measure of switch costs as it takes into account the inter-stimulus interval. Thus, it was expected that there would be a switch cost above and beyond the task performance cost. Based of the results of Logan (2004), it was predicted that reaction times for the span + single task or combined condition (as described in Experiments 1 and 2) would be significantly faster than the perform condition.

Given the relationship between working memory and task-switching seen in previous research (Mayr & Kliegl, 2000; Rubinstein et al., 2001; Sohn & Anderson, 2001), it was predicted that both the number of switches and the number of tasks to be remembered would significantly increase switch costs reflected by slower reaction times.

5.2 Method

5.2.1 Design

Experiment 3 employed a 3-way within-subjects repeated measures design. The first within-subjects variable was task-type (2 levels; Span and Perform). The second within-subjects variable was number of switches, (4 levels; ranging between 3 and 6) while the third within-subjects variable was List-Length (3 levels: List-Length 4, 5, and 6). There were two dependent variables: reaction time measured in milliseconds and accuracy measured as the proportion of correct responses.

5.2.2 Stimuli and Apparatus

The stimuli and apparatus in Experiment 3 were identical to that of Experiment 1 and 2 with the following exceptions. In Experiment 3, an additional task was added which was a position judgment (i.e. is the target stimuli Above or Under the shape). Each task was paired with a unique symbol that represented the task in the test phase. The shapes included a triangle, square, circle, diamond, cross and X. Task pairs were presented as the shape on the left side of the computer screen and the task name on the right. Thus if a square was chosen to represent the Odd/Even task, it was presented on the computer screen as □= Odd/Even. During the test phase, the shape was positioned in the centre of the screen with a target stimuli (1-9 presented as either number or words) presented either above or below the shape. The shape task combinations were randomly assigned and varied across trials.

5.2.3 Procedure

As with Experiments 1 and 2, each list involved a study phase and a test phase. Each study list was preceded by a display which included the following statement: "STUDY: Task List-Length *N*," where *N* ranged from 4 to 6 and represented the number of task shape pairs to be recalled. Each task name was presented for 1000ms and was followed by a 1000ms blank screen before the next task name was presented.

When presented in the target list, each target stimulus on the test list was exposed for 4000ms or until the participant responded. The participants used the same keys as in Experiment 1 and 2 with the addition of the position judgment and this was mapped onto the keys A and U on the keyboard to represent the Above/Under task decision (refer to Figure 1). The mapping of response categories onto keys was consistent with the ordering of the words in the task names.

Like Experiments 1 and 2, Experiment 3 consisted of both a span and perform condition. In the study phase component of the span condition, participants were presented with shape-task pairs. Each shape was associated with a particular task for that trial. In the test phase, participants were presented with the shape by itself and were required to press the key that represented that task. For example, if a triangle was presented with the task Odd/Even in the study phase, then in the test phase when the triangle appeared, the participant would be required to press the O button which represented the Odd/Even decision.

In the perform condition, as with the previous experiments, there was a study list and a test list. The study list comprised pairs of words and shapes, and the participants were again required to remember these pairs for the test phase. In the test phase, participants were presented with a shape that appeared with either a number above or below it. Participants were required to use the shape to determine which task needed to be performed for the number.

Participants were given three practice trials prior to the commencement of the span and perform conditions to allow for familiarisation with the task. There were 54 trials in both the span and perform conditions. In total, there were 108 trials in this experiment.

5.3 Results

5.3.1 Accuracy

The proportion of trials in which participants achieved 100 percent accuracy was calculated for each participant for the memory span (Figure 13) and perform conditions (Figure 14), number of switches (3, 4, 5, or 6) and List-Length (4, 5, or 6). In Experiment 3, statistical analysis was divided into 3 components. This was to account for the fact that a List-Length of 4 could not accommodate 5 switches and that only List-Length 6 could accommodate 6 switches. Thus, separate analyses were conducted for List-Lengths 4, 5, and 6 across 3 and 4 switches and for List-Lengths 5 and 6 across 3, 4, and 5 switches. Finally, a one-way ANOVA was conducted to examine the influence of number of switches on recall in the List-Length 6 condition. The modified task-span procedure offered the opportunity to compare results for both accuracy and reaction time in two ways; by calculating accuracy and reaction times for trials performed perfectly (that is 100 percent accurate trials) and by examining the proportion of correct trials within a sequence.

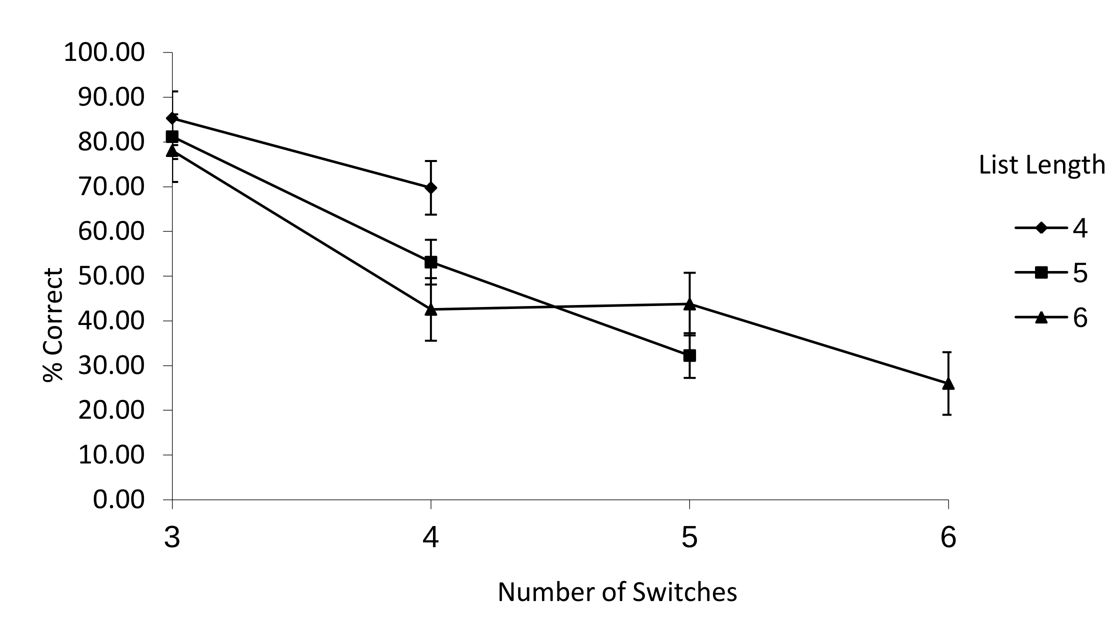

Figure 13. Proportion of 100 percent correct trials and standard error across the number of switches and List-Length for the memory span condition.

Three separate (a 2x3x2, a 2x2x3 and a 2x4) repeated measures ANOVAs were conducted for proportion of 100 percent correct trials. Pairwise comparisons were conducted using Bonferroni corrections. Figure 13 shows the mean proportion of 100 percent accurate trials for the memory span condition as a function of number of switches and List-Length. Figure 14 shows the mean proportion of 100 percent accurate trials for the perform condition as a function of number of switches and List-Length.

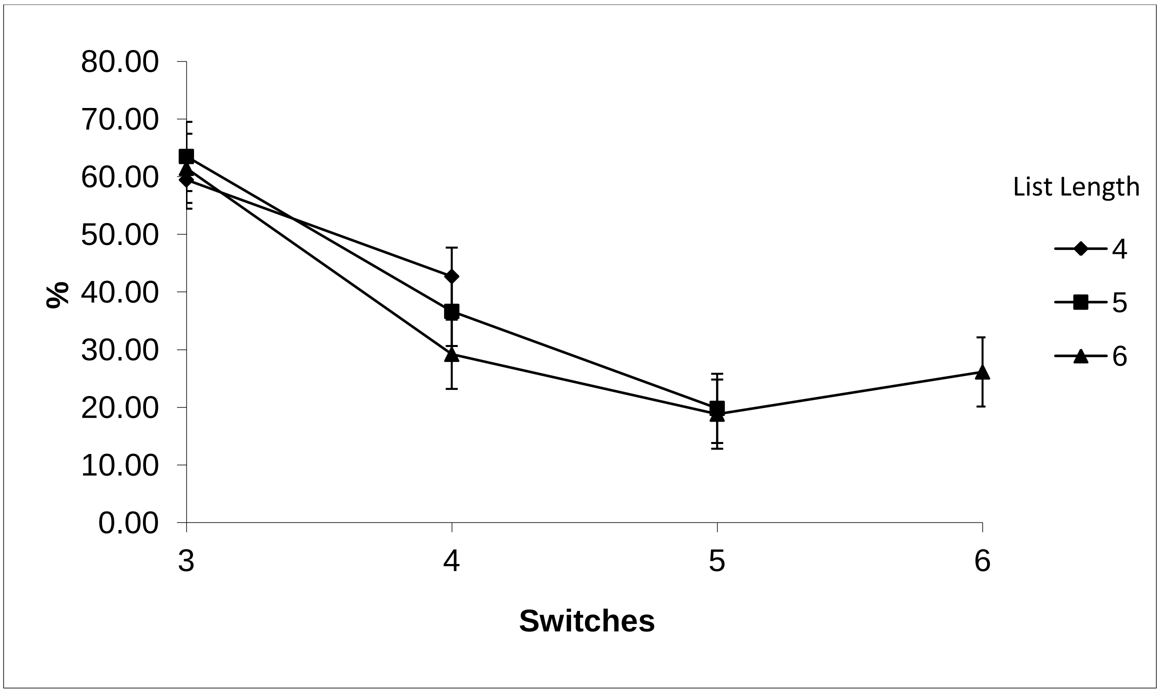

Figure 14. Proportion of 100 percent correct trials and standard error across the number of switches and List-Length for the perform condition.

5.3.1.1 Accuracy for 100 percent accurate trials

Accuracy results were compared for 100 percent accurate trials for both the span and perform conditions. When comparing List-Lengths 4, 5, and 6 across 3 and 4 switches there was a significant main effect for task type on proportion of trials 100 percent correct, $F_{(1,15)}=21.34$, $p<.01$ such that accuracy in the memory span condition was significantly higher than in perform the condition.

There was a significant main effect for List-Length, $F_{(1,15)}=5.69$, $p<.01$ such that accuracy for List-Length 4 was significantly higher than List-Length 6. There was also a significant main effect for switches, $F_{(1,15)}=93.08$, $p<.001$, such that accuracy was significantly higher for 3 switches as compared to 4 switches.

There was also a significant interaction between List-Length and number of switches, $F_{(1,15)}$=4.28, p<.05. Pairwise comparisons revealed that accuracy was significantly higher for the List-Length 4 switch 4 condition (M= .56 SE=.06) as compared to the List-Length 5 switch 4 condition (M=.48 SE=.05, $t_{(15)}$=2.82, p<.01). Further, accuracy was significantly higher for the List-Length 4 switch 4 condition (M= .56 SE=.06) as compared to the List-Length 6 switch 4 condition (M=.36 SE=.05, $t_{(15)}$=4.61, p<.001). Finally, accuracy was significantly higher for the List-Length 5 switch 4 condition (M= .45 SE=.05) as compared to the List-Length 6 switch 4 condition (M=.36 SE=.05, $t_{(15)}$=4.61, p<.05).

When comparing List-Lengths 5 and 6 across 3, 4, and 5 switches again there was a significant main effect for task type on proportion of trials that were performed with 100 percent accuracy, $F_{(1,15)}$=16.61, p<.01; accuracy in the memory span condition was significantly higher than in the perform condition.

As expected there was a significant main effect for the number of switches, $F_{(1,15)}$=51.66, p<.01 such that the accuracy for 3 switches was significantly higher than 4 switches and 5 switches. Further, accuracy was significantly higher for 4 switches than 5 switches. Again there was no main effect for List-Length nor were there any interactions.

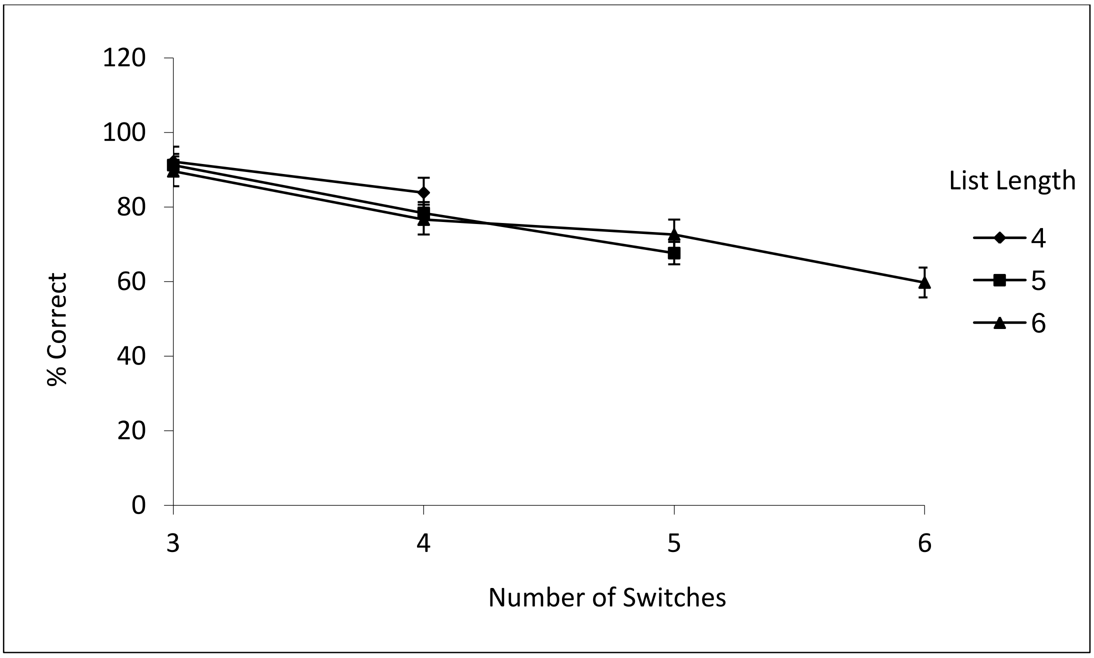

Figure 15. Proportion of correct trials and standard error across the number of switches and List-Length for the span condition.

When comparing task length 6 across 3, 4, 5, and 6 switches there was a significant main effect for task type, $F_{(1,15)}=11.23$, $p<.01$ such that accuracy was greater for the span condition than the perform condition. There was also a significant main effect for number of switches $F_{(1,15)}=14.63$, $p<.01$. There were no significant interaction effects.

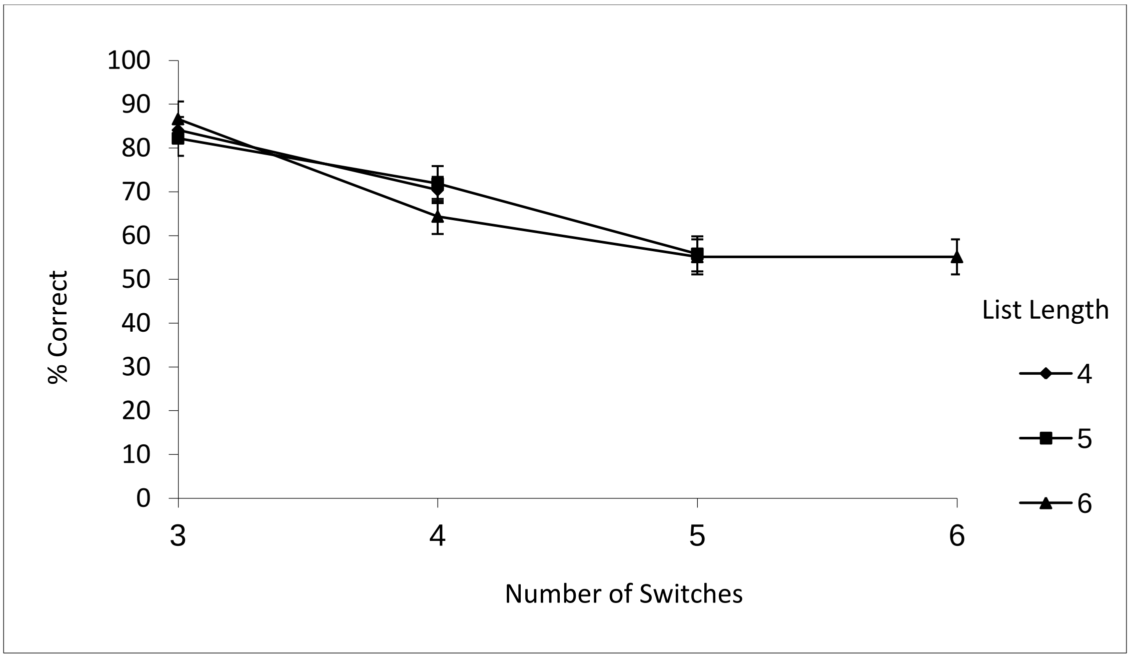

Figure 16. Proportion of correct trials and standard error across the number of switches and List-Length for the perform condition.

The accuracy results for the 100 percent accurate trials suggest that additional processing demands reduced accuracy. Further, unlike Experiment 2 where there were more complex patterns of chunking, the results using the modified task-span procedure yielded more conventional results. Accuracy decreased as the amount of information to be remembered increased. Finally, accuracy reduced as the List-Length increased.

5.3.1.2 Accuracy for Proportion of Correct Trials

The proportion of correct items within a sequence was calculated for both the span (Figure 15) and perform (Figure 16) conditions. Task-shape pairs were learned independent of sequence and this allowed accuracy to be measured in trials where 100 percent accuracy was not achieved.

When comparing List-Lengths 4, 5, and 6 across 3 and 4 switches there was a significant main effect for task type on proportion of items correct, $F_{(1,15)}=20.69$, $p<.001$ such that accuracy in the memory span condition was significantly higher than in perform condition.

As expected there was a significant main effect for the number of tasks, $F_{(1,15)}=61.49$, $p<.001$, such that the accuracy for 3 tasks was significantly higher than 4 tasks. There were no significant interactions, however, there was a trend approaching significance between task type and number of tasks ($p=.058$).

When comparing List-Lengths 5 and 6 across 3, 4, and 5 switches again there was a significant main effect for task type on proportion of items correct, $F_{(1,15)}=15.60$, $p<.01$ such that accuracy in the memory span condition was significantly higher than in perform condition.

As expected there was a significant main effect for the number of tasks within a sequence, $F_{(1,15)}=29.05$, $p<.001$ such that the accuracy for 3 tasks was significantly higher than accuracy for 4 tasks and accuracy for 4 tasks was significantly higher than accuracy for 5 tasks. Again there was no main effect for List-Length nor were there any interactions.

When comparing task length 6 across 3, 4, 5, and 6 switches there was a significant main effect for task type, $F_{(1,15)}=15.00$, $p<.01$. There was also a significant main effect for number of switches $F_{(1,15)}=13.30$, $p<.01$. There was a significant interaction between span perform and the number of switches. Subsequent pairwise comparisons revealed no significant differences between span and perform for 3 and 6 tasks, however there was a significant difference for 4 switches ($t_{(15)}$=3.61, p<.01) and 5 switches ($t_{(15)}$=4.63, p<.01).

Overall, the results using the alternate measure of accuracy are similar to those seen in the 100 percent accurate trials. Additional processing requirements (i.e. perform condition) resulted in reduced accuracy. Further, as the number of tasks to be recalled increased there was a reduction in accuracy of recall. Finally, accuracy also decreased as the List-Length increased.

5.3.2 Reaction Time

The mean reaction time of trials in which participants achieved 100 percent accuracy was calculated for each participant as a function of task type (memory span or perform), number of switches (3, 4, 5, or 6) and List-Length (4, 5, or 6). As with the accuracy component, the reaction time component of Experiment 3 analysis was divided into 3 components. Thus, separate analyses were conducted for List-Lengths 4, 5, and 6 across 3 and 4 switches and for List-Lengths 5 and 6 across 3, 4, and 5 switches. Finally, a one way ANOVA was conducted to examine the influence of number of switches (3, 4, 5, and 6) on recall in the List-Length 6 condition.

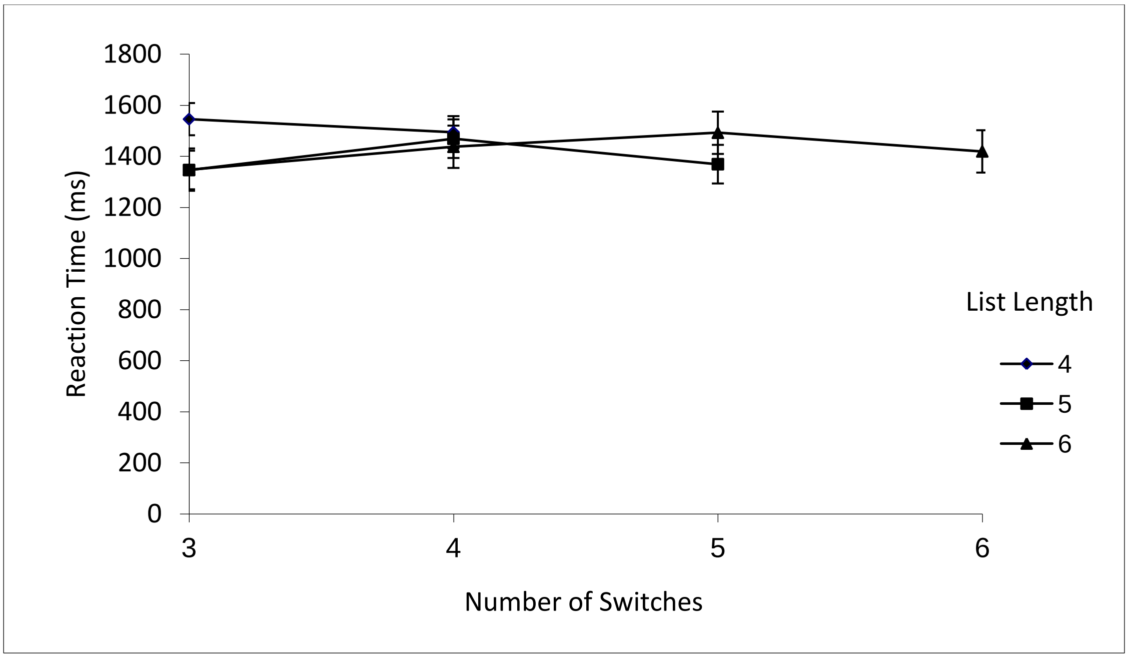

Figure 17. Mean reaction time (ms) and standard error for 100 percent correct trials across the number of switches and List-Length for the memory span condition.

A 2x3x2, 2x2x3 and a 2x4 repeated measures ANOVA was conducted for mean reaction time. Pairwise comparisons were conducted using Bonferroni corrections. Figure 17 shows the mean reaction time for 100 percent accurate trials for the memory span condition as a function of number of switches and List-Length. Figure 18 shows the mean reaction time for 100 percent accurate trials for the perform condition as a function of number of switches and List-Length.

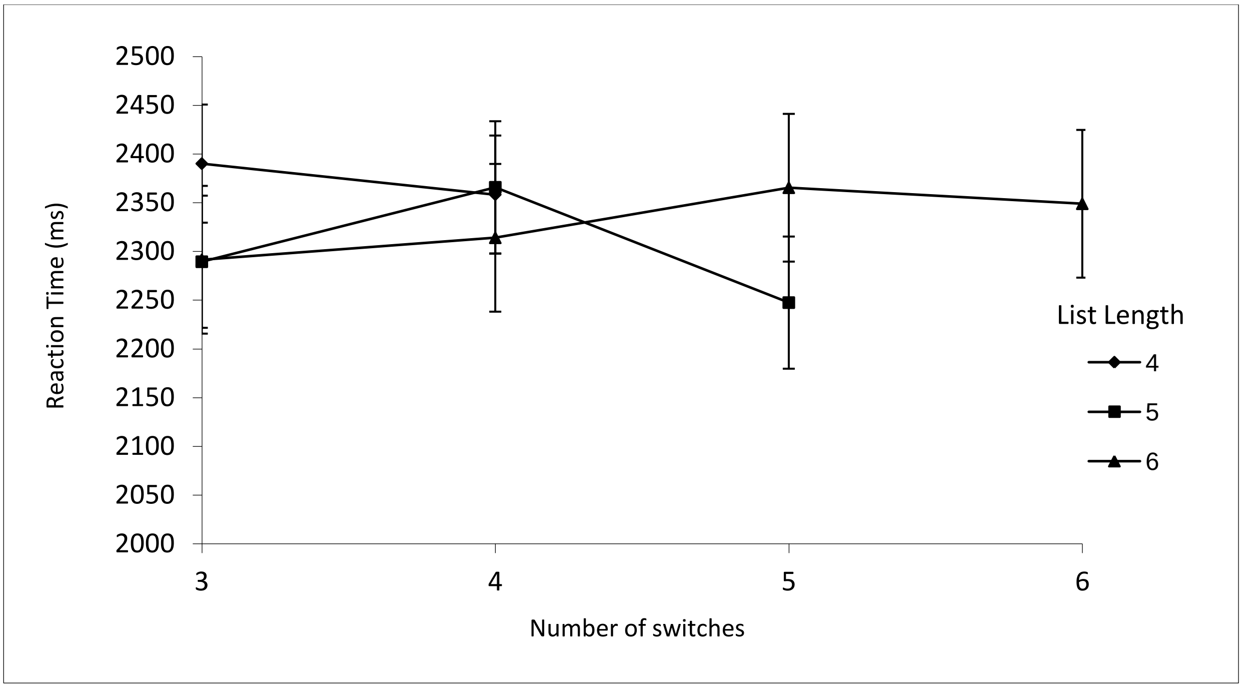

Figure 18. Mean reaction time (ms) and standard error of 100 percent correct trials across the number of switches and List-Length for the perform condition.

5.3.2.1 Reaction Time Results for 100 Percent Accurate Trials

Reaction time results were compared for 100 percent accurate trials. When comparing List-Lengths 4, 5, and 6 across 3 and 4 switches there was a significant main effect for task type on the reaction time of trials 100 percent correct, $F_{(1,11)}=122.76$, $p<.001$ such that reaction time in the memory span condition was significantly faster than in the perform condition. There was no significant difference in List-Length and number of tasks.

There was also a significant interaction between List-Length and number of switches, $F_{(1,15)}=5.50$, $p<.05$. Pairwise comparisons revealed that reaction time was significantly faster for the List-Length 5 switch 3 condition (M= 1879.32 SE=38.96) as compared to the List-Length 5 switch 4 condition (M=1999.24 SE=54.49, $t_{(15)}= -3.32$, $p<.01$).

When comparing List-Lengths 5 and 6 across 3, 4, and 5 switches again there was a significant main effect for task type on reaction times of trials 100 percent correct, $F_{(1,6)}=71.07$, $p<.001$ such that reaction times in the memory span condition were significantly faster than in the perform condition. There were no significant main effects for number of tasks or List-Length, nor were there any significant interactions.

When comparing task length 6 (both memory span and perform conditions) across 3, 4, 5, and 6 switches there was a significant main effect for task type, $F_{(1,3)}=58.51$, $p<.001$. There was no significant main effect for number of switches nor was there a significant interaction.

In summary, the reaction time data for the 100 percent accurate results suggest that the span condition was consistently faster than the perform condition. There were no significant effects for List-Length or number of switches. There were few significant interactions; the only one of note was that of List-Length 5 with 3 switches condition was significantly faster than the 4 switches condition. Overall, these results suggest that additional processing increases reaction time.

5.3.2.2 Reaction Time Results for Proportion of Correct Trials

The alternate measure of accuracy was used to compare reaction times. The combined (single task + memory span condition; Figure 19) and perform (Figure 20) conditions were compared across List-Lengths and number of switches. Comparing

List-Lengths 4, 5, and 6 across 3 and 4 switches revealed a significant main effect for number of tasks to be recalled within a sequence on reaction time, $F_{(1,15)}=13.36$, $p<.01$ such that reaction time for 3 switches was significantly faster than 4 switches.

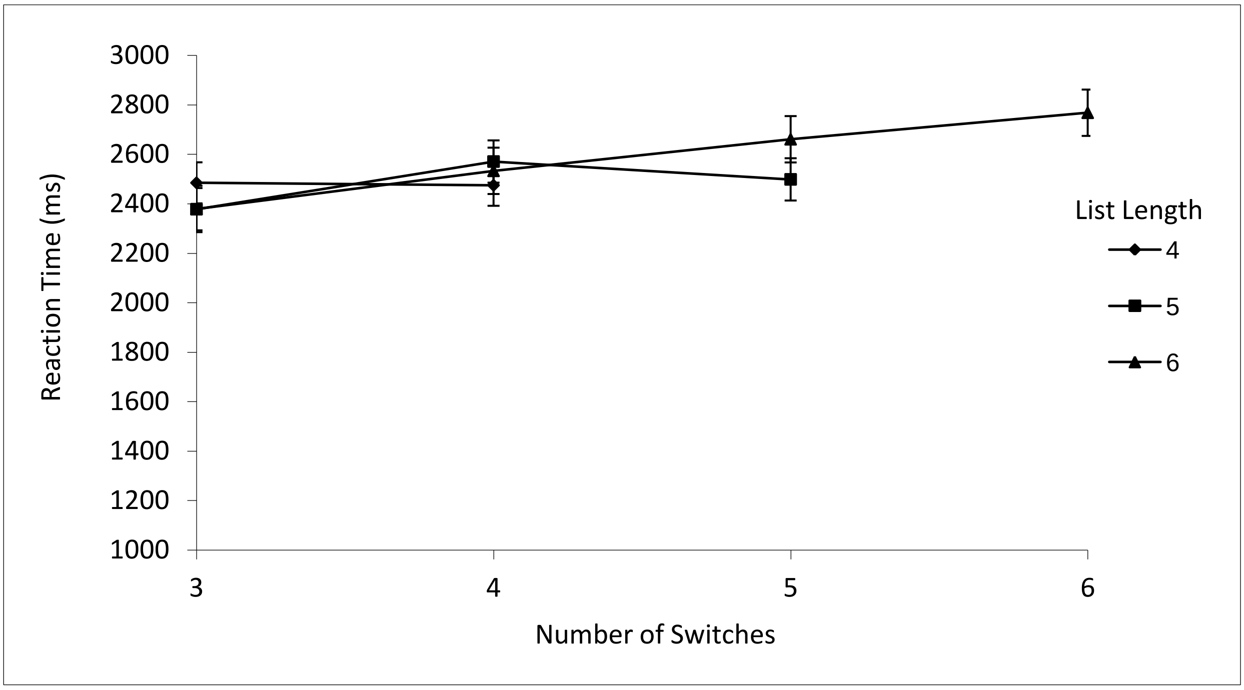

Figure 19. Mean reaction times (ms) and standard error for proportion of correct trials across the number of switches and List-Length for the combined memory and single task condition.

There was a significant interaction between List-Length and number of tasks, $F_{(1,15)}=4.09$, $p<.05$. Pairwise comparisons revealed that reaction times were significantly faster in the List-Length 5 switch 3 condition (M= 2348.95 SE=41.25) compared to the List-Length 5 switch 4 condition (M=2495.00 SE=53.79, $t_{(15)}= -4.11$, $p<.01$). Reaction times were significantly faster in the List-Length 6 switch 3 condition (M=2356.47 SE=45.17) compared to the List-Length 6 switch 4 condition (M=2476.39 SE=47.68, $t_{(15)}=-4.44$, $p<.001$). Reaction times were significantly slower in the List-Length 4 switch 3 condition (M=2438.81 SE=51.10) as compared to the List-Length 5 switch 3 condition (M=2348.95 SE=41.25, $t_{(15)}=2.89$, $p<.01$). Reaction times were significantly slower for the List-Length 4 switch 3 condition (M=2438.81 SE=51.10) as compared to the List-Length 6 switch 3 condition (M=2356.47 SE=45.17, $t_{(15)}$= 3.17, p<.01).

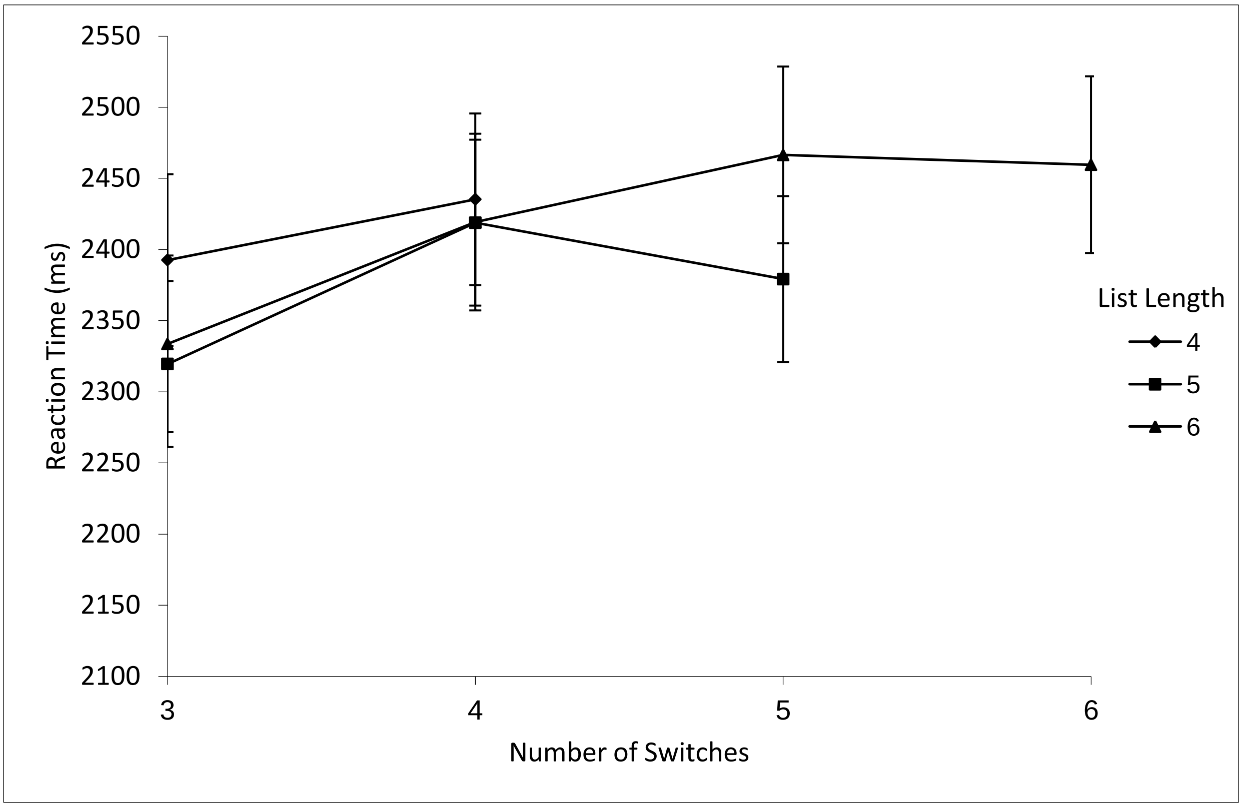

Figure 20. Mean reaction time (ms) and standard error for the proportion of correct trials across the number of switches and List-Length for the perform condition.

When comparing List-Lengths 5 and 6 across 3, 4, and 5 switches again there was a significant main effect for number of tasks on reaction time, $F_{(1,15)}$=14.30, p<.001 such that reaction times were significantly faster for 3 switches as compared to 4 switches. There was no significant difference in reaction time between 4 and 5 switches. There was no significant main effect for task type or List-Length.

There was a significant interaction between task-type and the number of tasks within a sequence $F_{(1,15)}=3.80$, $p<.05$. Pairwise comparisons revealed that reaction times were significantly faster for the span switch 3 condition (M= 2378.80 SE=62.45) as compared to the span switch 4 condition (M=2552.32 SE=78.06, $t_{(15)}=-5.26$, $p<.001$). Further, reaction times were significantly faster for the span switch 3 condition(M= 2378.80 SE=62.45) as compared to span switch 5 condition (M=2580.07 SE=100.32, $t_{(15)}=-3.84$, $p<.01$). Pairwise comparisons also revealed that reaction times were significantly faster for the perform switch 3 condition (M= 2326.63 SE=49.57) as compared to the perform switch 4 condition (M=2419.06 SE=55.46, $t_{(15)}=-3.42$, $p<.01$). Further, reaction times were significantly faster for the perform switch 3 condition (M= 2326.63 SE=49.57) as compared to perform switch 5 condition (M=2422.84 SE=50.90, $t_{(15)}=-2.43$, $p<.05$).

When comparing task length 6 across 3, 4, 5, and 6 switches, there was a significant main effect for number of tasks within a sequence $F_{(1,15)}=10.15$, $p<.01$ whereby reaction time for 3 switches was significantly faster than 6 switches. There was no main effect for task type. While there were no significant interactions, there was a trend across task type and number of tasks ($p=.057$).

Overall, the reaction time results of Experiment 3 suggest that when recall time is added to the time taken to perform a task (single task + memory span), the trade-off seen between processing and storage disappears. This is contrary to the work of Logan (2004) and suggests that there was no switch cost when switching between different tasks within the modified task-span procedure. Instead, the differences seen between the span and perform conditions are more likely to reflect the additional processing requirements seen in the perform condition. Finally, neither List-Length nor number of switches within a sequence significantly influenced reaction time.

5.4 Discussion

The aim of the third experiment was to examine the nature of capacity limitations in relation to both chunking and task switch load. Unlike both the first and second experiment, the third experiment used a modified version of the task-span procedure. The aim of Experiment 3 was threefold: first, to examine the role of working memory load on the time taken to flexibly switch between tasks; second to develop an improved measure of the reaction time costs associated with task-switching and finally to reduce the influence of chunking by creating symbol-task pairs that constituted chunks in themselves. Further, it allowed switch costs to be accounted for more accurately than the original task-span procedure (Logan, 2004; 2006). The shape in the task acted as a cue for the task that needed to be completed, so unlike the original task-span procedure, the modified task-span procedure did not allow for processing during the inter-stimulus interval.

5.4.1 The Processing Storage Trade-Off

Based on the results of Experiment 1 and 2 which revealed a trade-off between processing and storage, it was predicted that accuracy would be significantly greater in the span condition than the perform condition. The results of the current experiment revealed that accuracy was greater in the span condition as compared to the perform condition and this was consistent with the findings of Experiment 1 and 2. Accuracy for switch-length 3 varied across List-Lengths between 78 and 85 percent in the span condition but was reduced to between 59 and 64 percent in the perform condition, with an average difference between span and perform condition of 19 percent. Similar differences were seen across switch length 4 (19 percent) and switch length 5 (18.5 percent) conditions. Interestingly, only the switch-length 6 condition did not reveal a difference in accuracy between span and perform. This may be due to a floor effect whereby recall accuracy was reduced when working memory capacity was exhausted. As with Experiment 1 and 2, these findings were inconsistent with those proposed by Logan (2004; Experiment 1). He found a very small trade-off between accuracy and processing such that the memory span and perform conditions were essentially equivalent. However, the findings across all experiments of the current study suggest that additional processing requirements consistently resulted in reduced accuracy of sequences recalled regardless of varying degrees of difficulty or number of tasks to be recalled.

Collectively, the current series of experiments suggest that as processing and storage demands exceed a predetermined limit, an individual’s performance deteriorated. This was evident in both accuracy and reaction time data. In Experiment 3, shape-task associations were introduced as a way to control for chunking. This was done to account for the within sequence chunking that was seen in Experiment 2, where there was no relationship between the number of switches within a sequence and processing requirements. The shape-task pairs aimed to act as independent chunks whereby it was harder to chunk tasks together within the sequence. After controlling for chunking in this way, the results suggested that increases in the number of tasks to be recalled reduced the accuracy of recall across both the span and perform conditions. Thus, an increase in working memory load was detrimental to recall and recall was further reduced when an additional processing task was also required (i.e. in the perform condition).

The results of the current experiment are inconsistent with previous studies (Cochini et al., 2002) which have shown that the choice of tasks combined and not the overall cognitive demand of dual-task requirements determined whether or not performance would be impaired when there were additional processing requirements. Research has found that combining a verbal memory task with a visual memory task did not lead to a substantial drop in processing (Duff & Logie, 2001). The results of Experiment 1 suggested that as task difficulty increases, recall performance decreases. In addition, the results of Experiment 3 suggested that as the number of tasks to be recalled increases (independent of grouping) there is a reduction in recall accuracy in addition to slower reaction times. Although it does not contradict the argument that there are less costs when certain types of tasks are combined (i.e. verbal-verbal and visual-visual), it suggests that both additional processing requirements in terms of task difficulty and increased demands on working memory capacity can cause trade-offs between processing and storage.

The results of Experiment 3 suggest that there was generally an inverse relationship between accuracy and reaction time. Thus, as the number of tasks increased, accuracy decreased and response latency increased. The only exception was seen with reaction times when both List-Length and switch length were identical (i.e. List-Length 4, 4 switches condition). This supports the notion that working memory is time limited and additional activities (i.e. processing tasks) influence working memory capacity. This difference can be explained by the principles of rehearsal (Colom et al., 2006; Cowan, 2004), particularly the benefits gained during simpler span tasks such as in the memory span condition in the current series of experiments. Colom et al. argued that there may be a general component for maintaining information in an active and reliable state which is determined by the efficiency of working memory itself rather than by an individual's controlled attention ability. Additional processing requirements lower the reliability of temporarily stored information because these processing requirements remove a proportion of the capacity used for temporary maintenance. Thus, the concurrent processing requirements leave less capacity for temporary storage of information. This diminishes the reliability of the stored information, which in turn leads to a greater number of errors.

Simple tasks do not have additional processing requirements beyond those of keeping traces within working memory active. In contrast, complex tasks preclude rehearsal due to the concurrent processing component of the task. Additional processing requirements draw attention and processing capacity away from rehearsal and this reduces the capacity to rehearse. Indeed, from this perspective loss of information from working memory may be a result of memory traces or activation not being adequately refreshed, resulting in reduced recall of items. The results from this series of experiments suggest that trade-offs between processing and storage only influence working memory when a certain threshold is reached. From a theoretical perspective, if a central focus of attention could shift from the processing task to the activated memory representation of the items in the recall component of the task, then a processing and storage task can be completed successfully. When either processing demands or storage demands increase then working memory reaches capacity and accuracy of that information is reduced. The implications of the need to shift attention from storage tasks to processing tasks will be discussed in detail in a later section (Section 5.4.3).

In summary, the results of the current experiment suggest that there is a clear trade-off between processing and storage of information in working memory. The trade-off between processing and storage seen in the current series of studies supports theories that suggest that a single cognitive resource is used for both processing and storage of elements (Just & Carpenter, 1992; Newell, 1990) rather than a multi-component model of working memory (Duff & Logie, 2001). The results of Experiment 3 suggested that in addition to processing demands (as seen in Experiment 1), working memory demand (when chunking is controlled for) reduces accuracy and increases reaction time.

5.4.2 Capacity Limitations and the Modified Task-Span Procedure

Understanding working memory capacity in its purist form is an under researched area of working memory. Early work by Miller (1957) proposed that recall is limited to seven-chunks (or meaningful units). More recent research has proposed several opposing views about the nature of capacity limitations. Some theories have suggested that capacity is limited by the amount of time elapsed rather than by the number of items that can be held simultaneously (e.g. Baddeley, 1986) while others suggest that there are no capacity limits but only constraints such as scheduling conflicts in performance and strategies required to deal with them. Some theories suggest that there are multiple, separate capacity limits depending on the type of material presented while others suggest there are no separate limits for storage versus processing (Daneman & Carpenter, 1980; Halford et al., 1998). Finally, some theories propose that capacity limits are completely task specific, with no way to extract a general estimate (Cowan, 1999). These studies have generally shown that working memory capacity may indeed be substantially less than originally proposed by Miller. Indeed, most recent research has suggested that working memory capacity is closer to four chunks (Cowan, 1999; Halford et al., 1998). Experiment 3 aimed to further examine the nature of capacity limitations and it was proposed that larger numbers of task-shape pairs presented at the time of encoding would result in a reduction in recall by limiting the sequencing and organisational factors seen in Experiment 2. By providing cue-task combinations, it would make forming chunks within a sequence more difficult.

The current findings support the idea that a four-chunk limit is most accurate in closely constrained circumstances (Cowan, 1999). In other circumstances, processing strategies can increase the amount of information that can be recalled (as seen in Experiment 2). Cowan (1999) suggested that a limit can only be predicted after considering what constitutes an independent chunk of information. The current experiment attempted to minimize the influence of organisation factors by creating associations between symbol and task. These associations were complex and as such, they minimised the influence of multi-task chunks. Further, the role of rehearsal and sequencing was minimised. This was done by changing list order, so that the task presentation order was varied between the study and test list. In the current study the span condition was considered as a pure recall condition as there were no additional processing requirements required to perform the task. The results of the current study suggest that within the span condition recall was reliably 4 items. Accuracy at 4 items was around 55 percent, however, it dropped sharply to 38 percent when the List-Length was 5. These results support the suggestion that working memory capacity is limited to around 4 items when organisational factors are controlled.

Interestingly, capacity was not limited by the number of shape-task pairs as expected and there was substantial variation in performance when the number of tasks within the sequence differed from the number of shape-task associations. Thus, when the number of switches was 4, as with Experiment 2, accuracy was higher for List-Length 4 than List-Length 5 and 6 and similarly accuracy was higher for List-Length 5 than List-Length 6. These findings suggest that working memory capacity is not only determined by the amount of information to be held but also in the way this information is retrieved. Additional tasks outside the perceptual set (as discussed in Experiment 2) interfere with recall. This supports the notion that both conscious grouping (chunking) and subconscious perceptual processes determine working memory capacity. Some theorists have argued that capacity of working memory span tasks that assess working memory are complex and often multiply determined (Lustig et al., 2001). Working memory span tasks have multiple study and test trials and participants are therefore required to manage both recall of upcoming trials and interference from previously presented trials, thus stopping interference at the time of recall (May et al., 1999). It could be argued that the incomplete sets present interference. The larger the incomplete set, the more tasks that interfere with recall. Lustig et al. (2001) found that processes that underlie interference are critical in determining span scores. They termed this proactive interference.

The results of Experiment 3 were consistent with Experiment 2 and suggested that when chunks occur during practice and study, they may evolve into more complex data structures such as templates. This allows information to be rapidly recorded into slots within that template (Gobet, 2000). As discussed in detail in Experiment 2, a template is created when numerous tasks are presented; the template in the current experiment is based not on well learned associations between tasks but instead as a limiter within the entire series of five tasks. The slots are rapidly filled with tasks within each perceptual set. Additional tasks that do not fit within the template interfere with recall. Thus, it is a combination of the use of templates and interference of tasks outside of the template that determines the amount of information recalled.

The current findings can also be explained from a relational complexity perspective (Halford et al., 1998). While Halford and colleagues (Halford et al., 1998) suggested that storage was limited to about four items, an additional parallel limit was proposed based on processing, in which the complexity of relations between items being processed was limited to four dimensions in adults. Within processing, complexity is defined as the number of related dimensions or sources of variation, that is, the complexity of a cognitive process is the number of interacting variables that must be represented in parallel to implement a process. In Experiment 3, the overall accuracy on tasks in both span and perform conditions was lower than in Experiment 2 for the same number of items to be recalled and the same list. For example, for switches 4 List-Length 4, accuracy was 96 percent in the span condition and 83 percent in the perform condition in Experiment 2 compared to 70 percent in the span condition and 43 percent in the perform condition in Experiment 3. It can be argued that by introducing shape-task associations, the complexity of the storage task increased and therefore accuracy was reduced. Furthermore, the difference in accuracy seen between the span and perform conditions in Experiment 3 was greater than Experiment 2. For example, for the switches 4 List-Length 4 condition, the difference in accuracy between the span and perform condition is 13 percent in Experiment 2 as compared to 27 percent in Experiment 3. Given that the processing tasks remained constant across these experiments, it can be argued that the reduction in accuracy was due to a more complex memory component. These findings imply that the traditional approach for defining limitations is inappropriate for processing capacity, and that the limit is defined by the number of independent components, rather than purely the amount of information in working memory.

The findings of Experiment 3 suggest that the mechanisms involved in perceptual processes exist independent of inter-item chunking. The modified task-span procedure used in Experiment 3 aimed to limit the amount of inter-item chunking by introducing an additional layer of task complexity by creating within-item associations. Despite this modification, items external to what was defined in Experiment 2 as the perceptual set continued to cause interference. The current series of experiments suggest that multiple process are involved in recall from working memory at both a conscious and a sub-conscious level and the relationship between these processes requires further exploration in future research.

5.4.3 Task-Switching and the Modified Task-span Procedure

The modified task-span procedure is designed to be a more accurate measure of the time taken to switch between tasks. Unlike the original task-span procedure

(Logan, 2004), the modified task-span procedure presents a cue (the shape) with the target that aimed to capture time in the inter stimulus interval. It was therefore predicted that reaction time in the memory span + single task or combined condition would be significantly faster than the perform condition and that this would reflect switch costs.

Despite this modification, the results of Experiment 3 supported findings from Experiment 1 and Experiment 2 and were not consistent with Logan’s (2004) work. It can be argued that Logan’s (2004) measurement of switch costs, that is, the addition of single task reaction time to the corresponding span task, may not be the most accurate measure of switch costs. Logan (2006) subsequently acknowledged the limitations of the task-span procedure in its original form and suggested that there may be a more valid measure of switch costs and retrieval time, by comparing switch trials to non-switch trials. He suggested that the underlying principles of the subtractive method Logan (2004) used to estimate switch costs in the task-span procedure were not valid (Logan, 2006).

The minimal switch costs seen between tasks in the current experiment can also be explained by the idea that switch costs are typically larger when switches are less frequent and given at infrequent intervals (Mayr, 2006; Schneider & Logan, 2006). The difference between predictable and unpredictable switches was examined in the work by Schneider & Logan (2006) who looked at transition frequency in explicitly cued task-switching. They found that switch costs were smallest when alterations were frequent and largest when task repetitions were infrequent. In a similar study, Mayr (2006) suggested that individuals modulate their switching behaviour as a function of switch probability. They found that the cue switch costs increased and task-switch costs decreased as a function of switch probability. Methodologically, the current series of studies used consistent frequent switches between test stimuli which resulted in each switch being predictable. It was an underlying assumption that each task had to be different from both the task before and the task after. Thus, the minimal switch costs seen in the current experiment can be explained by predictable switches.

An alternative explanation is that switch costs are not seen between tasks, instead they are seen in alterations between storage and processing components within the task, and that this trade-off represents true switch costs. This is supported by several studies (Barrouillett et al., 2007; Bunting & Cowan, 2005) that acknowledge the role of attention on working memory. It perhaps provides the most unified theory on the role of task-switching on working memory. Bunting and Cowan (2005) suggested that attention and awareness form the basis of one type of working memory storage. They argued that processing difficulty can impede working memory recall as it draws attention away from a storage function. Thus, in the current experiment when a participant was required to make a decision in the perform condition their attention was drawn away from the storage component. This switching between processing and storage requirements in the perform condition resulted in costs in terms of both reduced accuracy and increased reaction time. Collectively, the findings of the current series of experiments support the notion that task-switching occurs between the processing and storage components of the task-span procedure and not between different task types as originally proposed by Logan (2004; 2006).

Further support for the role of attention in working memory is derived from the finding in Experiment 3 that reaction times were faster when the number of switches and List-Length were congruent. Additional tasks that fell out of this set within a List-Length may have acted as interference or as distractors. Thus, when there was congruence between the number of switches and List-Length (i.e. List-Length 4 with 4 switches), interference was minimised and reaction times were faster. The congruence effect is well established within the attention literature but has yet to be established within the working memory literature. The congruence effect offers insight into cognitive control processes and their relationship to working memory capacity. Further research is required to clarify the role of congruence in working memory.

Several studies have found that both task duration and cognitive load may determine the concurrent maintenance of information in working memory (Barrouillet et al., 2004; 2007; Barrouillet & Camos, 2001; Gavens & Barrouillet, 2004). The results of the current study are consistent with the notion of a sequential time based function of working memory in which storage and processing rely on a single and general purpose attentional resource needed to run executive processes devoted to consistently maintaining and modifying representations (Barrouillett et al., 2007). The addition of a processing task and increased working memory load in the current study resulted in slower reaction times and reduced accuracy. The formalised version of this theory is known as the Time-Based Resource Sharing (TBRS) model which encompasses the role of attention and acknowledges the relationship between processing and storage. This theory suggests that in most working memory span tasks, both processing and maintenance of information rely on the same limited resource and that many of the elementary cognitive steps involved in both storage and processing can only take place one at a time. Items in the focus of attention receive activation but when attention is switched away, this activation suffers from time-related decay. Thus, successful task performance relies on a rapid and incessant switching of attention from processing to maintenance (Barrouillett et al., 2004).

Expanding on this, Liefooghe (2008) argued that the effect of task-switching on concurrent maintenance of information in working memory did not rely on task specific reconfiguration processes but rather from a combination of simple and more fundamental processes. Thus, reduced accuracy and slower reaction times when an additional processing task was added to a storage task (the perform condition), may have related to the rapid and incessant switching of attention between the fundamental processing and maintenance components of the task.

Experiment 3 also aimed to directly measure the influence of working memory load on task-switching. The modified task-span procedure used in Experiment 3 allowed the number of switches in this paradigm to remain constant within a List-Length while varying the working memory component was varied. For example, when the List-Length was 6 there were 5 switches and the number of tasks within a List-Length could vary between 3 and 6. Given the relationship between working memory and task-switching (Mayr & Kliegl, 2000; Rubinstein, et al., 2001; Sohn & Anderson, 2001), it was predicted that both the number of switches and the number of tasks to be remembered would increase switch costs as reflected by reduced accuracy and slower reaction times.

The current study found no influence for the number of switches within a trial (List-Length), however the number of tasks required to be performed within a sequence influenced recall accuracy. It can be presumed that by increasing the working memory load while keeping the total switch load constant, working memory load increased switch costs. The current results support the findings of Rogers and Monsell (1995) who suggested that an alteration trial placed more demands on working memory: individuals must remember more than one task in an alteration trial but only one in repetition trials therefore some of the switch cost can be explained by an increase in working memory load. Thus, increased working memory demands and processing requirements in the current study resulted in reduced accuracy of recall and increased response latencies.

As discussed previously in Experiments 1 and 2, some researchers have argued that task-set reconfiguration operates within working memory while others have suggested that it involves processes outside of working memory as well as processes that operate in working memory. Still others suggest that switch costs reflect long-term memory processes that are outside working memory and that switch costs reflect interference from past task sets or past associations to the stimuli under different task sets (Allport et al., 1994; Allport & Wylie, 2000). If it is argued that switching occurs between storage and processing elements of the task-span procedure, then the current findings support the suggestion that task-switching occurs within working memory. The results suggested that increased working memory and processing demands are central to switch costs and as the number of tasks to be recalled increases, accuracy decreases and response latency increases.

5.4.4 Conclusion

In summary, Experiment 3 aimed to devise a more accurate measure of switch costs that accounted for the influence of preparatory factors that occur within a typical task-span procedure. The results of Experiment 3 revealed that there are limitations in the task-span procedure as conceptualised by Logan (2004) and that switch costs may not be best defined as the switch between different task-types within a sequence but instead by the switch between processing and storage/maintenance activities. Finally, the results of Experiment 3 (as with Experiments 1 and 2) support theories that suggest there is a general capacity within working memory involved in both storage and processing as well as task-switching (Barrouillett et al., 2007; Bunting & Cowan, 2005).

General Discussion

An extensive review of the literature suggests that there is still very little consensus regarding the underlying processes of working memory. Specifically, the nature of capacity limitations and strategic factors that influence its capacity, the relationship between processing and storage, and the relationship between attention and working memory are still unresolved. This thesis aimed to integrate and test theories of working memory by utilizing both established and modified paradigms. The overarching objective was to describe the relationship between additional processing requirements, organisational factors such as chunking, and task-switching, on the ability to hold information in working memory.

6.1 Processing and Storage

Previous studies that have examined the relationship between processing and storage have shown mixed results. Some researchers have demonstrated a trade-off between processing and storage and suggested that there is a central capacity or processing limit in working memory (Just & Carpenter, 1992; Newell, 1990). Others have suggested that there is no or minimal trade-off between processing and storage and therefore processing and storage are independent processes (Engle et al., 1999; Kane et al., 2001; Kieras et al., 1999). The results of the three experiments in the current study consistently found a trade-off between processing and storage in working memory. Thus, when a task required both processing and storage, accuracy was reduced and response latency increased. In addition, working memory capacity was also related to the difficulty of the processing task. In Experiment 1, task difficulty influenced working memory capacity such that accuracy was higher in the easy condition than the hard condition. These findings suggest that both additional processing and processing difficulty contributed to working memory recall.

Interestingly, the influence of task difficulty on recall varied as a function of List-Length resulting in accuracy being greater in the hard condition than the easy condition at List-Length 4; however at List-Length 6, accuracy was greater for the easy condition than the hard condition. As working memory load increased additional processing requirements (as seen in the hard condition) only influenced recall accuracy once the threshold of working memory capacity had been reached. This threshold was seen when comparing the memory span to the perform condition and the easy to the hard condition in Experiment 1. Thus, when storage and processing requirements were low, minimal strain was exerted on the central processor and the two elements (storage and processing) of the task could be completed with relative ease. However, as overall task complexity increased, by increasing working memory demand or processing load, performance was reduced.

From a theoretical perspective, the current results support theories that suggest that there is a central resource which is responsible for both the processing and storage of information in working memory tasks (Anderson & Matessa, 1997; Cowan, 1999; Daneman & Carpenter, 1980; Just & Carpenter, 1992; Lovett et al., 1999). The current series of studies refute Baddeley and colleague's (Baddeley, 2002; Baddeley & Hitch, 1974) initial theory which suggested that there are two distinct slave systems (visual and verbal) are responsible for rehearsal and storage, and a central executive that is responsible for the co-ordination of these two systems. Focusing on the phonological loop, Baddeley (2002) argued that this system consisted of two components: a phonological store and an articulatory rehearsal system. He suggested that traces within a store tended to decay over time unless information was refreshed by rehearsal (Baddeley & Hitch, 1974). The current findings (across all three experiments), suggest that additional processing tasks indeed impair recall. Baddeley's theory could accommodate the present results by arguing that the reduction in performance between the span (recall alone task) and the perform (recall and processing task) conditions could be the result of the central executive's inability to divide attention and also switch between tasks. However, this distinction cannot explain the difference in accuracy and reaction time between easy and hard tasks seen in Experiment 1. While Baddeley and colleagues suggested that imposing a secondary attention demanding task had an effect on encoding but not on recall performance (Baddeley et al., 1984; Craik et al., 1996), the results of the current study demonstrated that additional processing tasks and processing difficulty clearly influenced the recall of items from working memory.

More recently, Baddeley added the episodic buffer to his model of working memory (Baddeley, 2000; 2002). The episodic buffer is assumed to be a limited capacity storage system capable of integrating information from a variety of sources. He argued that it is controlled by the central executive, which is able to retrieve information from the store in the form of conscious awareness, or reflect on that information and, where necessary, manipulate and modify it. The buffer is episodic in the sense that it holds episodes whereby information is integrated across space and potentially across time. Although this explains the role of processing difficulty on recall, it is poorly defined and seems less plausible than a more unified model that acknowledges the role of attention as a form of temporary storage.

The findings of the current series of studies are consistent with theories that acknowledge attention as a form of storage in working memory. Cowan (1999) suggested that three components contribute to working memory. Working memory information comes from hierarchically arranged processes consisting of long-term memory, the subset of long term memory that is currently activated, and the subset of the activated component of memory that is currently in the focus of attention. He argued that attention is conjointly driven by voluntarily controlled processes and an involuntary attentional orienting system (Cowan, 1988; 1995; 1999). The information in the current focus is the most readily accessible information in working memory. Information that is activated, though not to the extent of conscious awareness, can also be retrieved reliably, albeit with a slightly longer delay. Essentially, attention is a limited capacity system such that only four chunks can be held in memory at any one time.

Activation, however, is time limited whereby activation of information within working memory will fade unless reactivated through rehearsal (Cowan, 1999). Thus, the trade-off between processing and storage seen in the current study could be explained by acknowledging the role of attention in storage. Cowan suggested that attention should be considered as a form of storage and that in the absence of being refreshed, items (or memory traces) outside the focus of attention will decay. He proposed that additional processing requirements shifted the focus of attention away from the rehearsal of memory traces and resulted in a reduction in recall. The current findings are consistent with the notion of a focus of attention that acts as a form of storage and suggest that introducing additional processing requirements reduce recall accuracy. In the span condition, attention is focused on the task of maintenance and rehearsal alone leading to higher accuracy in recall. In contrast, in the perform condition, task performance required attention to be drawn away from the maintenance or rehearsal of the task sequence in working memory. When attention is drawn to the processing task, the subsequent items within the list are not adequately refreshed and the reliability of the held information is reduced. This was seen in Experiment 1 whereby the focus of attention acted as form of storage and the complexity of processing requirements influenced recall capacity whereby additional complexity was found to compromise maintenance activities and consequently recall.

The current findings can also be conceptualised within models that view working memory as part of a larger cognitive architecture (Lovett et al., 1999). According to ACT-R theory (Anderson & Matessa, 1997; Anderson et al., 1998; Lovett et al., 1999), there are two ways to define working memory in a theoretical context. Firstly, to equate working memory to content that is being maintained during processing (e.g. the elements that are representing the memory items in the working memory task). Thus, working memory is not a specific system in itself, but instead is a series of declarative nodes that are highly activated because they are linked to the current system goals (source activation). According to this definition, working memory consists of mechanisms acting on declarative memory, learning decay, and attentional activation (Lovett et al., 1999). Secondly, working memory can also be defined by the processes which enable elements to be concurrently maintained. From this perspective, the emphasis is on the attentional activation mechanisms that differentially activate items relevant to current task goals. This process-oriented definition of working memory complements the content-oriented version whereby nodes in the highly activated subset of declarative memory receive an important part of their activation from the process that spreads the activation. Thus, working memory is conceptualised as a cognitive resource that can be allocated to enable the maintenance and processing of information, is inherently limited, and differs in supply across individuals. The current research supported the notion that additional processing requirements (either by the performance of additional processing tasks or by processing complexity) reduced the reliable recall of information from working memory.

The present series of studies found that working memory capacity is limited not only by the amount of information presented but also by the presence of additional processing requirements. In addition, the complexity of the processing task in dual-task situations reduced storage. The distinction between the span and perform conditions (across all three experiments) and the easy and hard spans (Experiment 1) provide strong support for the notion that a single capacity system is responsible for both storage and processing in working memory. The results of the current experiments suggest that when the load for either of these is increased, there is a reduction in the overall performance of the system. The strong trade-offs between processing and storage seen in the current series of experiments provided compelling evidence for models that propose there is a single resource responsible for both these processes. Recent theories have suggested that attention modulates this relationship and given that it is inherently defined as a limited resource this could explain current findings. Despite these promising results the factors that modulate the trade-off between processing and storage remain unclear. Further study is required to examine the role of processing requirements. Specifically processing complexity (task difficulty) and whether differences in recall due to a time-based decay or factors such as interference between internal representations. This will help to identify factors involved in the process of maintaining information in working memory.

6.2 The Influence of Organisational Factors on Working Memory Capacity

Organisational processes exert a large influence on memory, both in remembering novel information over short intervals and in learning material over a longer term (Bower, 1972). However, relatively few recent studies have examined how these factors influence working memory capacity. This series of experiments aimed to examine the role of grouping on working memory capacity. Experiment 2 of this study specifically examined the role of chunking on working memory capacity and task-switching. This was done by manipulating not only the List-Length (as in Experiment 1) but also the number of tasks to be recalled within that List-Length. Experiment 3 used a modified version of the task-span procedure to reduce the influence of chunking by creating symbol-task pairs that constituted chunks in themselves. Each symbol-task pairing acted as an independent chunk and therefore it was argued that this additional storage requirement would reduce the ability to form inter-item associations. This enabled the interaction between span-length and chunk-length to be examined more effectively.

Chunking involves the reorganization of material into familiar or regular structures and has been found to improve working memory performance (Bor et al., 2004; Ericcson et al., 1980). In short-term memory tasks items can be grouped using temporal, rhythmic, and/or spatial structures imposed either externally or by an individual’s internalized strategies. In Experiment 2 there was an interaction between List-Length and the number of item types (types of switches) within a list such that recall was better when there was greater uniformity between List-Length and the number of tasks within that list. For example, accuracy was greater for List-Length 4, 4 switches than for List-Length 4, 3 switches. Thus, even though there were fewer tasks to remember within the 3 switches condition, the uniformity between List-Length and switches in the List-Length 4, 4 switches condition aided recall. Results from Experiment 2 indicated that both strategic and perceptual processes acted in unison to influence the storage of information. Although strategic processes such as chunking are well established in the literature, the effects of perceptual processes are less well known. Perceptual processes here are believed to be unconscious processes which minimize interference from items that sit outside the perceptual set. These occur secondary to templates being created in long-term memory. Templates are hypothesised to be created at an unconscious level when each task has been presented once. The templates consist of slots that are rapidly filled with tasks within each perceptual set. Additional tasks that do not fit within the template interfere with recall. Thus, it is a combination of the use of templates and interference of tasks outside of the template that determines the amount of information recalled.

Experiment 3 imposed associations between task and shape with the aim of reducing the influence of chunking. Even with this manipulation the results indicated that items outside the perceptual set produced interference and reduced recall. The results of Experiment 3 provided strong support for the role of interference within working memory storage above and beyond the effect of time-related decay. There was often no difference in the number of items to be encoded and rehearsed, but there was a difference in the accuracy of recall. For example accuracy was higher in the List-Length 4, 4 switches condition than the List-Length 5, 4 switches condition.

Indeed under both these conditions the number of items to be encoded and subsequently rehearsed was 4. However, the number of items that needed to be recalled from memory was either 4 or 5 (with one of the items being recalled twice). The significant difference between these two conditions cannot be exclusively explained by a time-related decay mechanism within working memory. As suggested earlier and consistent with the findings of Experiment 2, tasks outside a perceptual set increase the amount of interference and reduce the number of tasks that can be recalled. The results of the current series of studies strongly suggest that both time-based and interference-based mechanisms are involved in the forgetting of information from working memory.

From a theoretical perspective, researchers have argued that forgetting can occur secondary to time-related activation decay (Baddeley & Logie, 1999; Cowan 1999; Cowan, et al., 1997), efficiency of controlled attentional processes and limits in the availability of activation (Lovett et al., 1999; Just & Carpenter, 1992), due to limits in processing speed and efficiency (Barnard, 1999; Kieras et al., 1999; Salthouse, 1996), or due to the complexity of the information to be remembered (Halford et al., 1998). The current findings indicated that both time-related decay and interference processes determine working memory capacity. This notion is consistent with Cowan (1999) who suggested that different limits apply to different aspects of working memory. Consequently, the focus of attention is capacity limited, whereas activation of information is time limited. Thus, items outside of the perceptual set (Experiments 2 and 3) interfere with accurate recall and this implicates attentional processes. In contrast, the distinction between easy and hard spans (Experiment 1) implicate a time based decay mechanism whereby hard tasks take longer to complete and therefore less resources are available to maintain/refresh information within working memory.

Evidence from the current series of experiments revealed that various factors influence working memory capacity. These include the organisational factors outlined above and the complexity of processing and storage relationships discussed earlier. These factors determine relational complexity (Halford et al., 1998) defined as the complexity of the storage relationship including associations, complexity of information to be remembered, processing complexity, and structural factors which enable both controlled chunking and perceptual processes.

6.3 Working Memory and Task-switching

The relationship between working memory and the ability to switch between various tasks allows researchers to examine the influence of cognitive control of attention on working memory (Barrouillett et al., 2007; Bunting & Cowan, 2005; Logan, 2004). The final aim of this series of experiments was to examine the role of task-switching on working memory. The three studies aimed to examine the influence of task difficulty and working memory load in both the task-span procedure and the modified task-span procedure. Experiment 1 examined the influence of processing difficulty and the relationship between working memory and task-switching. Experiment 2 explored the influence of the number of active representations on working memory. Finally, Experiment 3 used a modified version of the task-span procedure to examine the role of working memory load on the time taken to flexibly switch between tasks, improve the measure of the reaction time costs associated with task-switching, and to reduce the influence of chunking by creating symbol-task pairs.

Overall, the findings from the current series of experiments were inconsistent with the work of Logan (2004). The present findings question the validity of the task-span procedure as a measure of switch cost. It can be argued that Logan's (2004) measurement of switch costs (i.e. the addition of single task reaction time to the corresponding span task) may not be the most accurate measure of switch costs. Logan (2006) acknowledged that the underlying subtractive method he (Logan, 2004) used to estimate switch costs in the task-span procedure were not valid (Logan, 2006). All experiments in the current study found no switch costs between the span and perform conditions even when the preparatory effects in the inter-stimulus interval were accounted for (Experiment 3).

The minimal switch costs seen between tasks in the current experiment can be explained by the idea that switch costs are larger when switches are less frequent and given at infrequent intervals (Mayr, 2006; Schneider & Logan, 2006). Methodologically, the current series of studies used consistent frequent switches between test stimuli which resulted in each switch being predictable. It was an underlying assumption that each task had to be different from both the task before and the task after and this may have influenced the magnitude of switch costs.

Perhaps the most viable explanation for the current findings is that switch costs are not seen between tasks, instead they are seen in alterations between storage and processing of information and that this trade-off represents true switch costs. This is supported by several studies (Barrouillett et al., 2007; Bunting & Cowan, 2005) that acknowledge the role of attention on working memory. This explanation provides the most unified theory on the role of task-switching on working memory. Bunting and Cowan (2005) suggested that attention and awareness form the basis of one type of working memory storage. They argued that processing difficulty can impede working memory recall as it draws attention away from a storage function. Thus, in the current experiment when a participant was required to make a decision in the perform condition, their attention was drawn away from the storage component. This switching between processing and storage requirements in the perform condition resulted in costs in terms of both reduced accuracy and increased response latencies. Additional support for the role of attention is derived from the finding in Experiment 3, where reaction times were faster when the number of switches and List-Length were congruent. Additional tasks that fell out of this set within a List-Length may have acted as interference. Thus, when the number of switches and List-Length (i.e. List-Length 4, 4 switches) were congruent, interference was minimised and faster reaction times were seen.

Several studies have found that both task duration and cognitive load influence the concurrent maintenance of information in working memory (Barrouillett et al., 2004; 2007). The results of the current study are consistent with the notion that storage and processing rely on a single attentional resource. This resource is used to control the executive processes devoted to maintaining and modifying representations (Barrouillett et al., 2007). The addition of a processing task and increased working memory load (independent of chunking) in the current study resulted in slower reaction times and reduced accuracy. Switching between processing and storage activities prevent information being refreshed within working memory and represent a task switch-cost.

The interaction between working memory and task-switching continues to pose a theoretical conundrum. Some research suggests that reconfiguration is a process that operates within working memory while others argue that task-set reconfiguration involves processes outside of working memory as well as processes that operate in working memory (Logan & Gordan, 2001; Merian, 2000). Still others suggest that switch costs reflect long-term memory processes that operate outside working memory and are secondary to interference from past task sets (Allport et al., 1994; Allport & Wylie, 2000). Experiments 2 and 3 aimed to directly measure the influence of working memory load on task-switching. The procedure used in Experiments 2 and 3 allowed the number of switches in this paradigm to remain constant within a List-Length while varying the working memory component of the task. For example, in List-Length 6 there were consistently 5 switches as each task was different from the preceding task. In contrast, the number of tasks that made up a List-Length could vary between 3 and 6. For example, the List-Length 6, 5 switches condition comprised Odd/Even, High/Low, Big/Small, Red/Green, High/Low while the List-Length 6, 3 switch condition comprised High/Low, Big/Small, Red/Green, High/Low, Big/Small, Red/Green. It was predicted that both the number of switches and the number of tasks to be remembered would increase switch costs reflected by slower reaction times.

Overall, Experiment 2 found no influence of the number of switches within a sequence (List-Length), however Experiment 3 found an effect for the number of tasks performed within a sequence. It can be argued (after controlling for chunking) that by increasing the working memory load while keeping the total switch load constant, working memory load increased switch costs. The current results support the findings of Rogers and Monsell (1995) who suggested that an alteration trial placed more demands on working memory: individuals must remember more than one task in an alteration trial but only one in repetition trials therefore some switch cost can be explained by an increase in working memory load. Consequently, increased working memory demands and processing requirements resulted in reduced accuracy of recall and increased response latencies.

Collectively, the current findings suggest that there are limitations in the task-span procedure as conceptualised by Logan (2004). All three experiments in the current thesis found no switch costs between tasks even when the preparatory effects were accounted for (Experiment 3). This suggests that switch costs may not be best defined as the switch between different task-types within a sequence, but instead by the switch between processing and storage/maintenance activities. The current study also examined the interaction between working memory and task-switching. Experiments 2 found no influence for the number of switches within a sequence and therefore did not support the role of working memory within task-switching. However, the results of Experiment 3 suggested that after controlling for chunking, the number of tasks in working memory did influence task-switch costs. This suggests that working memory has a general capacity that accounts for storage and processing as well as task-switching. It can be presumed (after controlling for chunking) that by increasing the working memory load while keeping the total switch load constant, working memory load increased switch costs. Future research should aim to distinguish between the processing/storage trade-off and task switch costs and whether these differ in the task-span or modified task-span procedure. This will have significant ramifications for the processing and storage literature, task-switching literature and models of working memory as a whole.

6.4 Limitations

There are several limitations to the current series of studies. First and foremost, are the limitations associated with the modified task-span procedure. The modified task-span procedure is a difficult task and may not be applicable, without further simplification, to the wider community. Participants in the current study consisted of undergraduate and postgraduate students who were likely to have at least average to high average level of intellectual functioning and therefore were able to perform the task adequately. A sample reflective of the broader community may have yielded different results especially considering the literature regarding individual differences within working memory (Conway & Engle, 1994; Engle et al., 1999), and the relationship between working memory and factors such as reasoning and intelligence (Bunting, 2006).

The results of Experiment 1 suggested that processing complexity of the additional task reduced the recall of information from working memory. Thus, processing complexity decreased the availability of resources in working memory for maintenance activities. A limitation of the current series of studies is that the processing complexity finding of Experiment 1 was not calculated into the construction of Experiments 2 and 3. The majority of models covered within the current study do not implicate processing complexity as a factor that determines working memory capacity. This important finding has not been examined extensively in the working memory literature and should be incorporated into future research.

A common methodological limitation within the working memory literature is that as tasks became progressively more difficult (as a result of increased processing demands and the amount of information to be recalled within a sequence), recall accuracy is reduced. Reaction time measures in the current study should be interpreted with caution due to large ceiling effects. There were fewer accurate trials at the longer List-Lengths where reaction times could be calculated. This is likely to have underrepresented true reaction time figures. The exception to this was in Experiment 3 where reaction times could still be calculated even when 100 percent accuracy was not achieved. This is a major advantage of the modified task-span procedure over the original task-span procedure proposed by Logan (2004).

When comparing the current research methodology to that of the original work using the task-span procedure (Logan, 2004), there was a large difference in the amount of practice trials given to the participants. This may, in part, account for the variation in the findings between the studies. With more practice and fewer tasks, it is likely that task rules would be consolidated into long-term memory and this may be able to account for the lack of difference seen between the storage and processing tasks reported by Logan (2004).

6.5 Conclusion

In summary, the present series of experiments examined the various underlying assumptions of working memory. Specifically, this research demonstrated that the amount of information held may not be the only factor that determines working memory capacity. Indeed, there is a clear trade-off between processing and storage and processing complexity also determines working memory capacity.

Furthermore, there are two types of processes that act on working memory, both conscious chunking and perceptual processes that may act at a subconscious level. Finally, the current study showed that the relationship between working memory and task-switching is modulated by the nature of the working memory task. The current body of work has extended knowledge regarding the processes implicated in working memory, the influence of additional processing requirements on capacity, and how attention modulates working memory capacity.

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Appendix A: Participant Information and Consent Form

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study examining the role of working memory in completing changing tasks. We are often required to remember a number of things at one time, hold them in mind and use these memories to complete tasks. For example, when cooking without using a recipe we need to recall each step of the process and execute each step in the correct sequence for the recipe to work. The concept of 'working memory' assumes that there is a system which temporarily stores information, and supports human thought processes. A fundamental property of working memory is that the number of items that can be remembered perfectly in order is limited to between three and seven items, depending on the nature of the items.

The ability to switch or change between tasks is the pinnacle of human cognition. It allows people to adapt to changing demands in the environment and it allows them to approach the same situation from different perspectives. However, it comes at a cost: switching takes time and produces interference. Researchers are still trying to interpret the nature of these costs. Many researchers interpret switch costs as reflecting the time required to reconfigure the cognitive system. However, they disagree on what is involved in reconfiguration.

In the Task-span procedure, the participants will be presented with a list of tasks to remember, followed by a list of items to perform the tasks on. The time it will take the participant to perform these tasks will be measured and the differences between the time it takes to perform these tasks in different conditions will be compared. There will be a number of task sequences to perform.

The tasks will consist of simple judgement, e.g.: is this an odd or even number, is the colour of the number red or blue, or is it a numeral or a written word.

I require participants whose ages range between 18-35 years who have normal or corrected-to-normal vision and no known neurological or neuropsychological condition. The participants will be requested to complete a computer based visual task which will require them to make responses to certain stimuli. It is anticipated that the computer task will require 45-minutes to complete. Participants will be allowed to have short breaks during testing sessions if they are thought to be fatigued by the tasks.

No findings which could identify any individual will be published. The anonymity of your participation will be protected by our procedure in which no names will be attached to any of the data collected; names will be replaced by code numbers. Only my supervisor and I will have access to this data which will be stored for five years as prescribed by the university regulations.

If you agree to participate you may withdraw at any time. If you decide to withdraw during the course of the research you may advise the researcher to cease. If after having completed the experiment you decide you no longer wish to be included in the research you may contact me and all your results will be removed.

CERTIFICATION BY SUBJECT

I,

of

certify that I am at least 18 years old* and that I am voluntarily giving my consent to participate in the study entitled:

Working Memory and Executive Control: The role of task complexity in the task-span procedure.

being conducted at Victoria University of Technology by: **Mr Sami Yamin**

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by:

Mr Sami Yamin

and that I freely consent to participation involving the use on me of these procedures.

Procedures:
- Use a computer to complete a working memory task of 45 minutes duration.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way.

I have been informed that the information I provide will be kept confidential.

Signed: **.. }**

Witness other than the researcher: **}** **Date: ....**

...}

Any queries about your participation in this project may be directed to the researcher (Name: Sami Yamin ph. 0409 406 253). If you have any queries or complaints about the way you have been treated, you may contact the Secretary, University Human Research Ethics Committee, Victoria University of Technology, PO Box 14428 MCMC, Melbourne, 8001 (telephone no: 03-9688 4710).

Appendix B: Ethics Approval Confirmation

MEMO

TO	Ms. Izabela Walters School of Psychology St Albans Park Campus	DATE	23/07/2007
FROM	Dr. Denise Charman Chair Faculty of Arts, Education & Human Development Human Research Ethics Committee		
SUBJECT	Ethics Application – HRETH 05/126		

Dear Ms. Walters,

Thank you for resubmitting this application for ethical approval of the project:

HRETH05/126 Working Memory and Executive Control: The role of task complexity in the task-span procedure.

The proposed research project has been accepted by the Chair, Arts, Education & Human Development Human Research Ethics Committee. Approval for this application has been granted from 23 July 2007 to 23 July 2009.

Please note that the Human Research Ethics Committee must be informed of the following: any changes to the approved research protocol, project timelines, any serious or unexpected adverse effects on participants, and unforeseen events that may affect continued ethical acceptability of the project. In these unlikely events, researchers must immediately cease all data collection until the Committee has approved the changes.

Continued approval of this research project by the Victoria University Human Research Ethics Committee (VUHREC) is conditional upon the provision of a report within 12 months of the above approval date (by **23 July 2008**) or upon the completion of the project (if earlier). A report proforma may be downloaded from the VUHREC web site at: http://research.vu.edu.au/hrec.php

If you have any queries, please do not hesitate to contact me on 9919 2536.

On behalf of the Committee, I wish you all the best for the conduct of the project.

Dr. Denise Charman
Chair

Faculty of Arts, Education & Human Development Human Research Ethics Committee