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What limits dual-tasking in working memory?
An investigation of the effect of sub-task demand on maintenance mechanisms employed during dual-tasking.

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PhD Psychology
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2016
Declaration

I, the author and candidate, hereby declare that:

- The thesis has been composed by the candidate.
- The work is the candidate’s own.
- The work has not been submitted for any other degree or professional qualification.

Signed: Date: 28/10/16
Acknowledgements

I would like to express my sincere gratitude to Robert Logie for his supervision of my undergraduate and postgraduate research, and for sharing his knowledge and experience with me. I am also grateful for my co-supervisors, Nelson Cowan and Candice Morey, who have provided insights and interpretations that would not have occurred to me otherwise. I would also like to thank my friends and colleagues, in particular my good friends Angela de Bruin and Stephen Rhodes who have made studying for my PhD a joy.

Finally, I would like to thank my mother and father. I owe everything I am, and everything I will every be, to them.
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Abstract

A number of models of working memory have been proposed since the seminal work of Baddeley and Hitch (1974) on the Multiple Component Model (MCM). Subsequent MCM research focussed on developing a theoretical framework based on modality-specific stores that can operate in parallel during dual-tasking. The MCM can be contrasted with theories of working memory that assume an attention-based domain-general shared resource responsible for both short term retention as well as on-line cognition, such as the Time-Based Resource Sharing (TBRS) model (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007). The TBRS model assumes that short-term memory is dependent on access to attention, and any diversion of attention results in increased forgetting. The model describes ‘refreshing’ as the process of serially bringing memory items briefly into the focus of attention. Barrouillet and colleagues have demonstrated in numerous studies that memory spans lower as the cognitive demand of the secondary task increases - findings that are incompatible with the MCM. However, Camos, Mora, and Oberauer (2011) found that both sub-vocal rehearsal (the verbal maintenance mechanism described in the MCM) and attention-based refreshing can be selectively employed by participants depending on task demands. Since TBRS methodology compares spans measured under different cognitive load levels that are the same for every participant, we were interested in whether ensuring that secondary task demand was set within each participant’s abilities would avoid ‘over-taxing’ the working memory system and reduce dual-task costs. Our initial investigations re-measured memory and
processing spans under dual-task conditions with secondary tasks’ demand titrated according to each individual’s measured ability (Experiments 1 and 2, and Doherty & Logie, 2016). We found that memory span was unaffected when processing demand was titrated, but that processing performance was lower when memory load was set above participants’ span. Subsequent experiments (3-8) investigated the effect of setting memory and processing load ‘below span’, ‘at span’, and ‘above span’ on memory and processing accuracy during dual-tasking. Overall it was found that processing resources can be reallocated to support memory performance but memory resources cannot be reallocated to support processing performance. We interpret the results as evidence for specialised memory resources and rehearsal mechanisms that can be supplemented by attention-based processes once storage capacities are exceeded. Experiments 6-8 aimed to encourage the use of phonological- or attention-based rehearsal mechanisms for verbal short term memory by either introducing articulatory suppression (AS) or shortening available encoding time for memory items. It was found that participants exhibited shared-resource effects when they completed the dual-task under AS, suggesting a shift to attention-based rehearsal. When encoding time was limited participants’ memory performance during dual-tasking was unaffected by concurrent processing load, suggesting the use of a rehearsal method which did not require access to attention. Experiment 9 investigated whether participants could dynamically allocate attention to one task or the other, and found that while ‘priority’ tasks received no benefit, non-priority tasks exhibited a marked decrement in performance. We conclude that the perceived incompatibility between the MCM and attention-based theories of working memory such as the TBRS model may be more apparent than real, and suggest that future research should incorporate procedures and methodological considerations that take into account findings from both literatures.
Lay Summary

‘Working memory’ refers to a mental space used to store and process temporary information. For example, driving a car while holding a conversation requires verbal memory (keeping track of the conversation), verbal processing (listening to and understanding the conversation), visual processing (keeping an eye on the road and responding to other drivers), and visual memory (remembering the positions of other cars in your mirrors). Working memory facilitates co-ordination of activities such as the one described above, and simple measures of working memory have been shown to predict a number of things including academic achievement.

However, researchers disagree on what limits working memory. Some argue for separate resources that are used to process or store information, for example a verbal store and a visual store. These specialised stores are said to hold information without any conscious effort, and different types of information do not interfere with information in different stores. In the driving example above, talking with a friend should have little impact on the ability to keep aware of other cars on the road.

Other researchers argue that memory and processing tasks all rely on a shared resource, and that an individual can only pay attention to one thing at a time and must rapidly switch their attention between tasks. The more the driver in the above example pays attention to the conversation the less attention they can pay to the road, and vice versa.

Our research investigated these two theories of working memory. We found that people can perform two tasks at the same time so long as these tasks are not too
demanding. Once people are asked to perform tasks beyond their abilities then one task can interfere with performance on another. For our example, when someone is driving on a quiet road they may be able to easily hold a conversation. However, when driving on a busy motorway their visual memory and processing may be over-taxed to the point that holding a conversation will severely affect their ability to drive.
Chapter 1

General Introduction
The term ‘working memory’ was first coined by Miller, Galanter, and Pribram (1960). Referring to the human ability to make, follow, and carry out plans, Miller et al. identified the need for a temporary workspace or ‘quick-access’ storage for such plans. The authors described our ability to switch between plans or goals and to maintain and resume interrupted plans as relying on this temporary storage system of ‘working memory’: the system that facilitates the co-ordination of multiple inputs, outputs, responses, inhibitions, goals and subgoals inherent to the most complex human thoughts and behaviours.

Working memory is thought to be responsible for the complex cognitive co-ordination necessary for everyday functioning. Generally, when referred to by both researchers and users of working memory research, tasks which call upon the cognitive mechanisms within working memory feature two components: a memory task and a cognitively demanding concurrent processing task. One of the most prevalent tasks in both working memory research and in psychological research as a whole, and as a result a perfect example of tasks which call upon both maintenance and on-line processing of temporary information, is the complex span task. Daneman and Carpenter’s (1980) original task required participants to process and respond to sentences while remembering the last word of each sentence for subsequent recall. Despite the description of the task as complex span, the simplicity of the task is matched only by its ability to predict other cognitive abilities, and as such the original task and variations of it have been a staple for psychological research in the years since its initial publication.

Measures of working memory are widely utilised in both research and clinical settings as valuable tools for assessing cognitive function, being a strong predictor of academic achievement (e.g. Cowan et al., 2005), an indicator of healthy (Johnson, Logie, & Brockmole, 2010) and pathological ageing (MacPherson, Della Sala, Logie,
1.1 Models used in the generation of hypotheses

Some long-standing conceptual approaches to working memory rely on the assumption of specialised subsystems, or ‘components’, which give rise to a cohesive concert of functions resulting in high-level cognitive behaviours (e.g. Baddeley & Hitch, 1974; Baddeley, 2012; Logie, 2011). Such theories focus on evidence from neuropsychology supporting the separation of working memory processes (see Gathercole, 1994, for a review) and comparisons of situations and task combinations in which short-term memory is resilient or vulnerable to decay. Successful performance on tasks such as complex span would result from greater ability to co-ordinate these multiple components, utilise their resources and functions efficiently, and preserve memory traces in the face of interference and/or decay.

Other theories are built upon the assumption that performance on short-term memory and processing tasks rely on access to a single domain-general attentional resource. Whether the role of attention is to provide temporary activation of long-term memory traces by bringing them into the focus of attention (e.g. Cowan, 2005;
1.1. Models used in the generation of hypotheses

Cowan, Rouder, Blume, & Saults, 2012) or to switch between concurrent tasks and provide activation of short-term memory traces (e.g. Barrouillet et al., 2004, 2007; Barrouillet & Camos, 2010), participants’ performance on tasks such as complex span are said to rely not only on successful co-ordination of subtasks but also the overall attentional capacity of an individual and the temporal constraints of the task.

There exist a large number of working memory theories with different emphases, research aims/motivations, experimental procedures, and research findings. As with many fields of research, working memory is characterised by debate. The literature features many conflicting models, yet efforts are being made to focus theories on explaining established working memory phenomena (see ‘Benchmarks for models of working memory’, Oberauer, 2014). The focus of the research presented here has been to contrast the Multiple Component Model (MCM) (Baddeley & Hitch, 1974; Baddeley, 2012; Logie, 2011) and the Time-Based Resource Sharing (TBRS) model (Barrouillet et al., 2004, 2007; Barrouillet & Camos, 2010).

Although a number of other models exist and will be discussed in relation to our findings, these two frameworks were used to generate hypotheses for the reported experiments since both assume decay to be the main cause of short-term forgetting, yet predict different mechanisms for the rehearsal/maintenance of memory items and therefore different patterns of performance in dual-tasking. While the MCM has a literature that dates back to Baddeley and Hitch’s (1974) seminal work, the TBRS model is a relatively recent theory. Since its original outline, the TBRS model has developed an extensive and internally-consistent literature that introduces concepts which concisely explains trade-offs during dual-tasking. However, a number of TBRS findings are inconsistent with core assumptions of multiple component theory. To non MCM and TBRS theorists the models may be considered to be quite similar (e.g. Oberauer, Farrell, Jarrold, & Lewandowsky, 2016), but it is the subtle differences
in model predictions that permit the comparisons which form the main foci of this thesis.

**The Multiple Component Model (MCM).**

The MCM refers to the co-ordinated deployment of multiple cognitive resources, each of which has its own limited capacity serving a specific function in on-line cognition. One component, the phonological loop, has been proposed for temporary storage of a sequence of phonological codes in serial order (e.g. Baddeley, 1992). A second component, the visual cache, is thought to store an array of visual items or a single visual item that may vary in complexity (Logie, 1995, 2003, 2011). In early versions of the model (Baddeley & Hitch, 1974; Baddeley, 1986) a central executive was thought to be a domain-general processing and control mechanism. Subsequently (Baddeley, 1996, 1998; Logie, 2016), there has been reference to a range of different executive functions, associated respectively with inhibition, updating, task switching (Miyake et al., 2000), dual-task co-ordination (Logie, Cocchini, Della Sala, & Baddeley, 2004), retrieval from long-term memory (Unsworth & Engle, 2007) and the generation and manipulation of mental images (Borst, Niven, & Logie, 2012; Van Der Meulen, Logie, & Della Sala, 2009). The central executive has since been suggested to be an emergent property of these multiple, separate functions and processes (Baddeley, 2002; Logie, 2016).

**Separating processing and storage.**

The MCM, in its early form, was born out of Baddeley and Hitch’s (1974) investigation of short-term memory’s involvement in reasoning and language comprehension. Up until that point many models of information processing (e.g. Atkinson & Shiffrin, 1971) had posited that both temporary storage and manipulation of infor-
1.1. Models used in the generation of hypotheses

Information was carried out in the same short-term store. Baddeley and Hitch noted that a number of previous studies had shown that the demand of a processing task could affect concurrent memory performance (e.g. Murdock, 1965) suggesting a shared resource, but that evidence was mixed and incompatible with a neuropsychological case study of the time in which a patient with severely limited short-term memory exhibited no other difficulties in learning, long-term memory, and language comprehension (Shallice & Warrington, 1970). Focusing on this incompatibility, Baddeley and Hitch argued that if both processing and storage of information taxed the same limited resource, then increasing the load of a memory task should affect participants’ performance on concurrent reasoning or language tasks.

In their investigations, Baddeley and Hitch (1974) found that memory load had no effect on reaction time for a reasoning task (i.e. reading statements and verifying them True or False) for low memory loads (3 items vs. 6), unless the participants were instructed that the memory task was more important than the sentence verification task. In the latter case, participants were informed that the processing task would not be scored if the memory items were not recalled with 100% accuracy. In another experiment, Baddeley and Hitch found that concurrent processing performance (sentence comprehension) was only affected by memory load for longer lists (six item lists elicited an effect, yet no difference was found between 1- and 2-item list conditions). Verbal processing (logical statement verification and sentence comprehension) was affected by phonological similarity in the same way as memory performance was known to be affected from prior research (Baddeley, 1966; Conrad & Hull, 1964). This suggested that sub-vocal articulation processes was used for the verbal reasoning task as well as for immediate verbal memory. The authors state that while this pattern of results could imply a “...workspace...which can be flexibly allocated either to storage or to processing” (Baddeley & Hitch, 1974, pp.57), the
magnitude of cross-task effects suggests that the mechanisms involved in temporary storage are only part of a larger system, as greater interference effects would be expected if both processing and storage tasks relied fully on the same limited-capacity resource.

Small storage/processing dual-task costs have been observed in other, more recent, studies. Duff and Logie (2001) compared single- and dual-task performance on verbal memory and verbal processing, with the demand of each task set at the measured capacity for memory and processing in each participant. They found that although performance on both tasks was poorer under dual-task conditions the average combined performance was \( \sim 70\% \) of single-task performance. The authors argued that if a single, shared resource supported both memory and processing, and performing two tasks at a level that demands all of the capacity of that shared resource during a single-task condition, then performance should be more substantially affected. The finding that performance remains well above chance on both tasks suggests that it is unlikely that both tasks are using the same resource but instead relying on separable mechanisms: the \( \sim 30\% \) cost to performance of introducing a secondary task is argued to be due to an attentional load of co-ordinating the concurrent performance of the two tasks.

A similar pattern was found by Duff and Logie (1999) for visual memory and processing items. Participants were required to click on simple visual items (a pool of six curved and straight lines in different orientations) that appeared in quick succession on a computer screen, and memorise the items presented to be recalled at the end of each trial. The difficulty of both tasks increased as more items were added - i.e. more memory items had to be stored and recalled while the speed of presentation of visual stimuli increased and so required quicker responses. No overall dual-task effect was found for memory accuracy (post-hoc analyses revealed a significant effect...
models used in the generation of hypotheses for 2-item lists only), and small decrements to processing performance were observed.

The studies mentioned above focus on the small costs of combining two tasks, with the small differences between single- and dual-task performance on both memory and processing tasks being argued as evidence for separable resources: if a single resource was fully taxed in the single-task conditions then the introduction of a secondary task should result in a severe detriment to performance. Duff and Logie (1999, 2001) argued that dual-task costs are related to a general cost of co-ordinating concurrent tasks, and that small drops in performance could have many causes beyond loss of access to a general purpose attentional resource.

Supporting the theory that dual-task costs arise from task co-ordination rather than access to a single shared resource, Logie et al. (2004) found evidence for a specific dual-task ability when comparing performance between Alzheimer’s Disease (AD) patients and healthy young and older adults. The memory task consisted of aurally presented digits with oral serial recall, while the secondary ‘processing’ task was visual perceptuo-motor tracking. AD patients’ performance in single-task was equated with that found for healthy young and older adults by setting the demand of each task (digit serial recall and a spatial tracking task) at the measured span levels for each participant.

Under dual-task conditions, the performance of the younger and older healthy adults did not differ, but the AD patients showed a substantial drop in performance. While patients’ memory performance was not affected by the introduction of the dual-task, the concurrent tracking task accuracy was affected. To confirm that patients’ poor dual-tasking performance was due to an inability to co-ordinate concurrent tasks rather than being the result of a lower general capacity, Logie et al. (2004) compared single-task memory and processing performance across multiple levels of demand and found that AD patients’ decrease in performance associated
with increasing demand of a single task was no greater for either task than that of the control groups. Moreover, the AD patients showed a dual-task cost even when the two tasks were set at very low demand levels that were well below the measured spans for each patient.

**Separate verbal and visual stores.**

The focus of MCM research has often been on the ‘slave systems’: modality specific stores with no ‘processing’ ability of their own. Typically, evidence for the existence of these stores is argued based on neuropsychological findings (Gathercole, 1994), case studies of individuals with specific short-term/working memory deficits (Shallice & Warrington, 1970; Baddeley & Wilson, 1988), and observed behavioural phenomena (discussed below).

**Phonological loop.** In addition to the evidence cited in the previous pages separating short-term memory for verbal items from concurrent processing (e.g. small dual-task costs: Duff & Logie, 1999, 2001), there exist two highly replicable behavioural phenomena that support the argument for specific verbal memory processes within the working memory system: the phonological similarity effect (Conrad & Hull, 1964) and the word length effect (Baddeley, Thomson, & Buchanan, 1975).

The phonological similarity effect refers to the observation that participants’ memory span is lower for lists of phonologically similar items compared to span calculated from lists of phonologically distinct items (Conrad & Hull, 1964; Baddeley, 1966). Baddeley (1966) argued that the effect is the result of increased reliance on acoustic coding of items for short-term storage, as similar effects were not observed for recall from long-term memory. The argument for an acoustic-based rehearsal and storage mechanisms is also supported by the observation that concurrent articulatory suppression (AS), which involves the participant repeating an irrelevant word while
performing immediate serial ordered recall, reduces memory span (Levy, 1971) by preventing sub-vocal rehearsal of items.

Regarding the word length effect, Baddeley et al. (1975) investigated whether the limits of short-term verbal memory were dependent on the number of discrete pieces of information (or ‘chunks’: see Miller, 1956), or due to limits imposed by speech coding. Comparing immediate serial ordered recall performance on lists of long and short words, Baddeley et al. (1975) found that the single-syllable words were recalled with greater accuracy than five-syllable words. However, most importantly, lists of words with the name number of syllables but with shorter pronunciation times were also recalled with greater accuracy than frequency-matched words with longer pronunciation times (examples from Baddeley et al., 1975, short: ‘wicket’, ‘ember’, ‘phallic’ vs. long: ‘Friday’, ‘coerce’, ‘harpoon’).1

Baddeley et al. (1975) reported that these effects were also independent of presentation time, and participants’ reading rates correlated highly with their memory span. The findings are argued as evidence for a specific phonological rehearsal mechanism, with limits in verbal working memory being due to loss of information that cannot be rehearsed in time to counteract decay. Longer words, and individual variation in articulatory speed, affect verbal memory performance as both can limit the amount of information that can be sub-vocally rehearsed within a limited time frame.

Further linking the word length effect to a discrete sub-vocal rehearsal mechanism, subsequent research by Baddeley, Lewis, and Vallar (1984) found that AS abolishes the word length effect for aurally presented items but that the phonologi-

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1This effect has been argued to be specific to the word sets used by Baddeley et al. (1975). Jalbert, Neath, Bireta, and Surprenant (2011) found that previous studies showing word length effects had confounded word length and orthographical neighbourhood size, with shorter words having larger neighbourhoods that may aid redintegration processes. Despite this challenge to the word length effect, the effect is one of the benchmarks that working memory models aim to explain (Lewandowsky & Farrell, 2008), and so the MCM account of the effect is the focus here.
1.1. Models used in the generation of hypotheses

cal similarity effect is still observed. This was argued as evidence for a separation of storage and rehearsal processes. Access to the phonological store is said to be automatic for aurally presented stimuli as evidenced by the disruptive effect of irrelevant speech on verbal memory span (e.g. Colle & Welsh, 1976; Salame & Baddeley, 1982). As such, aurally presented memory items remain vulnerable to the effects of phonological similarity since they gain automatic access to the phonological store despite concurrent AS. The word length effect is argued to be due to limitations in the speed of rehearsal in the phonological loop (as opposed to storage limitations), and AS is thought to prevent rehearsal and so abolishes the effect.

**Visuospatial sketchpad.** Complementing the phenomenological evidence for the phonological loop is a literature investigating mechanisms involved in memory for visual and spatial stimuli. The argument for a separate mechanism, or group of mechanisms, for short-term visual or spatial memory comes from double-dissociation studies such as Logie, Zucco, and Baddeley (1990). In this study it was found that memory for visual matrices was less affected by a concurrent arithmetic task than a verbal recognition task. Conversely, visual memory was more strongly affected by concurrent visual imagery task (mentally constructing images from verbal instructions) compared to performance on a verbal memory task.

Within the visuospatial domain, further dissociation has been made between memory for visual and spatial information (reviewed in Logie, 1995). Logie and Marchetti (1991) demonstrated a double dissociation between memory for visual information (coloured shades) that was disrupted by irrelevant pictures (line drawings of animals and objects) but not by arm movements, while memory for a sequence of spatial locations was disrupted by arm movements but not by irrelevant pictures. Additional evidence for separable visual and spatial resources can be found in the staggered development of children’s abilities in each type of memory task. Logie
1.1. Models used in the generation of hypotheses

and Pearson (1997) demonstrated that the capacities of visual and spatial memory increased across different age groups at different rates, with gains in span for visual patterns with age being greater than gains in memory for a series of spatial locations. Moreover, within each group, the correlations were low between spatial and visual memory spans suggesting separable storage and rehearsal mechanisms for each type of material.

While the capacity of the phonological loop can be linked to speed of articulation, a logical analogy for visual and spatial memory is not immediately apparent. One similarity between verbal and visual memory is the impact of visual similarity of stimuli. Hitch, Woodin, and Baker (1989) found that young (ages 8-11) children’s memory for pictures of objects was vulnerable to intrusions from and confusions among visually similar items. Also, Hitch et al. (1989) found that for older children this effect was only present under AS while phonological similarity effects were observed when participants were able to sub-vocally rehearse, suggesting an age-related change from a reliance on visual representations to the use of verbal codes.

Some characteristics of the limits of spatial memory have also been identified. For example, Cornoldi, Cortesi, and Preti (1991) reported that the complexity of movements had an impact on memory for spatial sequences, suggesting a use of spatial codes that is susceptible to domain-specific interference. Cornoldi et al.’s (1991) procedure involved articulatory suppression to prevent the use of verbal codes, while Smyth and Scholey (1992) found that participants’ articulation rate correlated with spatial span. Also, Smyth and Pendleton (1989) found that memory for hand movements to spatial targets differ in their sensitivity to spatial interference than hand movements alone. Smyth and Pendleton measured participants’ span for a series of hand configurations (e.g. splayed fingers, a fist, pointing up with palm facing the body, etc.), and for a series of spatial movements measured using a Corsi block task.
The authors found that memory for hand configurations was reduced by a simple motor task introduced in the retention interval while memory for spatial movements were not. Conversely, spatial memory was affected by a spatial tapping interference task, while participants’ memory for hand configurations was not. These findings support the existence of specific, separable ‘codes’ for spatial and motor movements, but that participants may rely on verbal mechanisms if they are available.

**Visual coding of verbal material.** Visual coding of verbal material, and the effects of visual similarity of words/letters on verbal recall has also been investigated in a number of studies. Logie, Della Sala, Wynn, and Baddeley (2000) found that participants’ verbal memory recall for visually and phonologically similar lists of items was poorer than only phonologically similar lists (examples from the paper: ‘fly’, ‘ply’, ‘cry’ vs. ‘guy’, ‘sigh’, ‘lie’). Similar results were found in a study by Saito, Logie, Morita, and Law (2008) utilising Japanese kanji for which both visual and verbal similarity of characters can be factorially manipulated: again, visual similarity effects were observed that were independent of the phonological similarity of items. This was true when scoring for order of recall, not just for scoring of items recalled. These findings suggest that participants use multiple resources for tasks, and that memory capacity may be dependent on the involvement of multiple processes (even for material considered to be within a certain ‘domain’).

**Summary of MCM.**

The MCM is a framework that attempts to explain phenomena such as domain-specific interference, AS, phonological similarity effects, etc., by separating working memory into specialised components. Major facets of the framework include separation of visual and verbal memory components (each with their own rehearsal mechanisms), and the separation of storage and processing/attention. Based on this
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framework, the MCM predicts small dual-task effects due to memory storage and rehearsal being separate from on-line processing.
The Time-Based Resource Sharing (TBRS) Model.

The Time-Based Resource Sharing (TBRS) model is an example of a theoretical framework that assumes a single, limited capacity general-purpose attention-based system that constrains on-line processing of information as well as the maintenance of temporary memory traces. The model states that the rate of short-term forgetting in participants is directly related to the attentional demand of concurrent tasks (termed ‘cognitive load’), since memory traces are assumed to decay when they are not re-activated or ‘refreshed’ by attention. Investigations of the effects of cognitive load and of the nature of attention-based refreshing have been two of the main foci of the TBRS literature, and are summarised here.

Cognitive load effects on memory performance.

Barrouillet and colleagues have demonstrated a cognitive load effect in a number of studies in the years since the publication of the original outline of their model (Barrouillet et al., 2004). Cognitive load refers to the attentional demand of a processing task during dual-tasking, specifically how much time the task captures attention. Barrouillet et al. (2004) described cognitive load (CL) using the following equation:

\[ CL = aN/T \]

Initially \( N \) referred to retrievals from long-term memory, but subsequent research expanded this to refer to any response-selection (Barrouillet & Camos, 2010). In the above equation, \( N \) refers to the number of responses required by the task, \( a \) refers to the difficulty of these responses (i.e. the time each response takes), and \( T \) refers to the total time available to make a response. The cognitive load of a task can therefore be increased by requiring a greater number of responses within the same
1.1. Models used in the generation of hypotheses

length of time, increasing the difficulty of these responses, or reducing the overall
time available to complete all responses.

Barrouillet and colleagues have demonstrated a cognitive load effect in a number
of studies, but the most comprehensive investigations are in Barrouillet et al. (2004)
and Barrouillet et al. (2007). Crucially, the TBRS model differentiates itself from
pure decay-based theories of short-term forgetting in working memory by stating that
longer retention intervals do not result in greater decay so long as the distractor task
has a low cognitive load and therefore allows sufficient time to ‘refresh’ of memory
traces. The independence of purely time-based decay and attentional switching/re-
source sharing related decay was demonstrated in Barrouillet et al. (2004), where
participants’ memory performance was poorer over shorter retention intervals than
when the total number of items to be processed remained the same (i.e. increasing
CL by reducing $T$ in the equation on page 19). Rather than simple time-related decay
(as argued by Towse, Hitch, & Hutton, 1998), within the TBRS model it is only this
competition that determines successful memory trace maintenance and retrieval and
that given sufficient access to an attentional resource, short-term forgetting should
be negligible.

Barrouillet et al. (2004) demonstrated how increasing the number of retrievals
($N$) significantly reduced memory performance in a span procedure. In a between-
participant design, the authors found that participants’ memory span for letters was
much lower when they were required to read ten numbers aloud during the retention
interval compared to when they read six numbers.

However, Barrouillet et al. (2007) also investigated the effect of increasing the
number of non-verbal processing items and found similar results. When participants
were required to judge the location of a dot (above vs. below a horizontal line
on the computer monitor), participants who were required to respond to a larger
number of stimuli demonstrated lower verbal memory span than those who were in less demanding conditions. The same effect was not observed using a simple reaction time (RT) task. The authors argue that the lack of cognitive load effect in the simple-RT conditions is due to the fact that such a task does not capture attention for a sizeable portion of the maintenance/refreshing interval and so increasing the number of items does not result in higher levels of forgetting (i.e. a suitably small $a$ in the cognitive load equation on page 19). Domain-general cognitive load effects have been replicated in other TBRS studies, e.g. Portrat, Barrouillet, and Camos (2008) report experiment in which increasing the cognitive load of a spatial processing task resulted in lower verbal memory spans.

The effect of long-term memory retrieval or response-selection time has also been extensively investigated. For example Barrouillet et al. (2007) investigated how keeping the number of responses constant whilst increasing the cognitive demand of the responses required by the task affected memory span. The experiment contrasted memory span across $N$-manipulated cognitive load conditions (an effect already established in Barrouillet et al., 2004), but also compared performance between participants who were required to make a simple spatial judgement - i.e. whether a presented number was positioned above or below the centre line on a monitor - and those who were to judge whether a presented number was odd or even (parity judgement). The difference in processing times between the two tasks revealed the differential attentional capture of the two tasks, with the longer reaction times of the parity judgement task being linked with lower concurrent memory spans than with the spatial judgement task.

**Refreshing.**

Within the TBRS framework, the effect of cognitive load on memory performance is argued to be the result of competing access to a domain-general attention resource.
This resource is said to ‘refresh’ decaying memory traces by bringing them into the focus of attention, and is argued to be a separate process from sub-vocal rehearsal (Camos, Lagner, & Barrouillet, 2009). Rather than being due to memory items simply being displaced by processing items, refreshing is argued to be a specific process of maintenance that can be actively or passively engaged (Camos et al., 2011; Vergauwe, Camos, & Barrouillet, 2014) and is only an effective method for stimuli that have some familiarity or semantic meaning (Ricker & Cowan, 2010; Vergauwe et al., 2014).

Raye, Johnson, Mitchell, Reeder, and Greene (2002) presented brain imaging evidence for refreshing as a specific process that briefly activates recently presented information. Activation of the dorsolateral prefrontal cortex was observed when participants were instructed to think of a word that was just presented, described as attention-based refreshing. In a follow-up study, Raye, Johnson, Mitchell, Greene, and Johnson (2007) directly compared this ‘refreshing’ behaviour to sub-vocal articulation (‘rehearsal’) of recently presented items. The authors found increased activation associated with refreshing in left Brodmann Area 9 (BA 9) middle frontal gyrus, and left BA 6 precentral and middle frontal gyri. In contrast, the rehearsal condition was associated with increased activation of BA 44 in the left inferior frontal gyrus and Broca’s area.

Hudjetz and Oberauer (2007) report evidence that supports the theory that refreshing and sub-vocal rehearsal may be separate processes. In the first of two experiments Hudjetz and Oberauer had groups of participants perform two versions of a reading span task, each with slow and fast presentation rates (i.e. short and long retention times). The first condition required participants to read sentences at their own pace and memorise the last word from each sentence. The second group of participants performed the same task, but their reading was set by a repeating tone
they were informed that they must speak each word in time with the tone with no pauses. It was found that participants’ memory span was higher in the slower/longer presentation condition than in the faster/shorter condition, and lower in participants who were required to read the sentences according to a set pace compared to those who read at their own pace. There was no interaction between these two effects. The fact that participants performed better over longer retention intervals conforms with the predictions of the TBRS model, since the number of sentences remained constant and so the cognitive load of the slower presentation condition would be lower than that of the faster/shorter condition.

In their second experiment, Hudjetz and Oberauer investigated how experiment-paced reading vs. natural reading affected participants’ ability to vocalise other words (i.e. ‘squeezing’ extra words between the words in presented sentences). Experiment-paced reading had a large effect on the number of words articulated by participants compared to natural reading, which the authors argued as evidence that participants performing under the former conditions would be almost entirely unable to sub-vocally rehearse memory items.

Hudjetz and Oberauer proposed that since there was no interaction between reading condition and retention time, with natural vs. experiment-paced reading having the same effect for both short and long intervals, that sub-vocal rehearsal is unlikely to be the sole available mechanism for maintenance. They state that due to the highly disruptive effect of the experiment-paced AS participants could not rely on sub-vocal rehearsal. Despite this, participants’ memory performance improved with longer retention intervals, in contradiction to the predictions of decay/task switching models (e.g. Towse et al., 1998). Hudjetz and Oberauer therefore conclude that participants must be relying on some other maintenance method other than sub-vocal rehearsal, such as the refreshing mechanism described by the TBRS model.
1.1. Models used in the generation of hypotheses

Hudjetz and Oberauer also note that since the same number of distractor items are present in the short vs. long presentation conditions the observed patterns of performance cannot be explained by purely interference-based models of short-term forgetting, but that such models may benefit from the inclusion of the refreshing mechanism described by the TBRS model.

The TBRS model describes refreshing as being a method of rehearsal that complements sub-vocal rehearsal, and that both mechanisms can be recruited to reduce time-based decay. Camos et al. (2009) stated that the disruptive effects of cognitive load (primarily affecting attention-based refreshing) and AS (primarily affecting sub-vocal rehearsal) are additive, proposing involvement of both processes in the maintenance of verbal memory items. The authors manipulated the availability of these two maintenance mechanisms by limiting access to attentional refreshing in Experiment 1 and by impeding sub-vocal rehearsal in Experiment 2. The first experiment had participants memorise a series of letters while either reading complete equations (e.g. ‘4 + 1 = 5’) or reading and answering incomplete equations (e.g. ‘4 + 1 = ?’). As with Hudjetz and Oberauer’s (2007) experiment, the number of utterances in each condition remained the same. However, the condition in which participants were required to provide their own answers to the equations necessitated a greater/longer capture of attention and therefore created a higher cognitive load. Experiment 2 required participants to hold a list of letters in memory while judging whether presented numbers were odd or even. One group responded via a key-press, whilst the second responded vocally. Camos et al. (2009) hypothesised that if both refreshing and sub-vocal rehearsal contribute to short-term memory maintenance, then both the attention capture of the parity judgement task (odd/even numbers) and the added AS introduced in the latter condition should result in poorer spans. Both Experiments 1 and 2 replicated the cognitive load effect described in previous
1.1. Models used in the generation of hypotheses

TBRS studies, while Experiment 2 demonstrated that the addition of AS component to the task reduced performance in addition to the cognitive load cost.

Camos et al.’s (2009) third experiment manipulated both attentional demand (simple-RT task vs. parity judgment of odd/even numbers) and access to phonological rehearsal processes (requiring keypresses or vocalisations to the simple-RT task, and requiring vocal vs. key-press responses to the parity judgement task). A fourth experiment compared performance on a simple detection task (detecting and responding to a target stimulus within a serially presented set) to performance on a more demanding mathematical verification task (confirming whether a presented digit was the sum of the two preceding digits). As with previous experiments, participants responded either via key-press or vocally. Replicating Hudjetz and Oberauer (2007), Camos et al. (2009) found that while both concurrent attentional demand (cognitive load) and AS had large negative effects on participants’ span, these effects did not interact. The authors cite this additive effect as evidence for two separate yet complementary mechanisms for short-term memory maintenance: an adaptive system of rehearsal/refreshing that can explain why performance does not drop to zero under AS or under dual-task conditions as rapid refreshing maintains memory traces when sub-vocal rehearsal can not.

To what extent the availability of these two mechanisms and their suitability to a task affects their recruitment was investigated by Camos et al. (2011). In their first experiment, memory performance with a concurrent choice-RT task was compared to performance alongside a location judgement task (parity judgement of whether a presented square appeared in the top or bottom half of the computer screen). Memory stimuli consisted of separate lists of phonologically similar words, and phonologically dissimilar words. Camos et al.’s (2011) hypothesis was that participants would tend towards attentional refreshing when task parameters permitted this (i.e. in the low
demand, or low cognitive load, condition) since this mechanism should be resilient to the effects of phonological similarity. Conversely, when attention is captured by the more demanding choice-RT task participants must rely on sub-vocal rehearsal, resulting in a greater effect of phonological similarity. The results revealed that the attentional demand of the task, and the phonological similarity of items, both affected recall performance. The phonological similarity effect was only present in the choice-RT condition, supporting the authors’ hypothesis that participants would tend towards refreshing as a maintenance mechanism when it is available.

Camos et al.’s (2011) first experiment did not instruct participants to use one method over the other. Using the same tasks as the experiment summarised above, two additional experiments investigated the extent of the phonological similarity effect when participants were specifically instructed to use sub-vocal rehearsal or to use attentional refreshing. Instructions for refreshing followed the procedure of Raye et al. (2007), in which participants were instructed to ‘think of’ the to-be-remembered items. Camos et al. found that the phonological similarity effect was only present when participants were instructed to utilise sub-vocal articulation as a rehearsal method: across both low and high concurrent demand conditions, the phonological similarity effect was not observed when participants were instructed to attentionally refresh items. These two additional experiments confirmed that participants’ use of refreshing or sub-vocal rehearsal does not depend solely on the demands of a task (reflecting an automatic selection of the most effective measure), but that participants can specifically select one method of rehearsal over another. Such findings may explain why phonological similarity effects and word length effects can be observed in some participants but not others (e.g. Logie, Della Sala, Laiacona, Chalmers, & Wynn, 1996).

The diversion of attention to support refreshing, and the resulting effect on per-
formance on concurrent processing tasks, is argued as further evidence for this mechanism. Vergauwe et al. (2014) investigated how increasing the demand of the memory task impacted performance on the concurrent ‘distractor’ task. In the first experiment, participants were presented with a series of spatial locations to memorise and recall. Encoding and retrieval phases were separated by a spatial judgement task (judging whether a line would fit between two dots). The authors found that as the memory load increased (i.e. longer sequences of spatial locations), participants’ responses to the processing task slowed. This effect was largest for the first processing item in the sequence. Vergauwe et al. provide an approximation of a 230ms ‘cost’ to the first-item RTs for each additional spatial location. However, the average RTs for subsequent processing items also increased linearly with each increase in memory load, calculated as approximately 57ms per item. These effects were replicated in follow-up experiments pairing a parity judgement task (identifying even and odd numbers presented on screen) with the aforementioned spatial location memory task.

Vergauwe et al. (2014) also investigated the effect of verbal memory load on participants’ processing RTs for the odd/even number parity judgement task. Under AS, the increases in RT were comparable to those observed with concurrent spatial memory load (∼220ms RT cost for the first processing items, and ∼40ms for subsequent items). However, when participants were not required to perform AS the effect of memory load on first-item and subsequent RTs only occurred for list lengths > 4. These effects were confirmed with a statistically significant between-experiment interaction. Vergauwe et al. proposed that for shorter lists participants rely on a specialised verbal memory store based on sub-vocal rehearsal, but that maintenance of longer lists they rely more heavily on attention based processes such as refreshing. The theory that refreshing processes are recruited when the phonological store is at capacity was further confirmed by comparing processing RTs for letters, mono-
1.1. Models used in the generation of hypotheses

syllabic words, and bisyllabic words: memory performance on bisyllabic words was poorer, and so the effect of memory load on processing RTs was observed for shorter lists of bisyllabic words than for lists of monosyllabic words or letters.

Evidence that supports refreshing as a specific process, and prevents the phenomena described above as being due to memory items being displaced from the focus of attention by processing tasks, is presented in the final experiment of Vergauwe et al. (2014). Ricker and Cowan (2010) established that novel visual stimuli could not be maintained with refreshing, reporting an effect of cognitive load only for familiar items (letters) but not for novel items (unconventional characters that were not easily nameable, consisting of Greek, Cyrrillic, Arabic letters, and unusual symbols). Vergauwe et al.’s final experiment demonstrated that lists consisting of ‘unrefreshable’ items did not elicit the same RT effects as regular letters, words, or visual locations (although the effect on first-item RTs remained, being attributed to consolidation-related activities).

Summary of TBRS model.

The TBRS model assumes that maintenance of memory items relies on access to a domain-general attention-based resource. While verbal memory is argued to have access to specific phonologically-based rehearsal mechanisms, performance is argued to rely heavily on the availability of attention to ‘refresh’ decaying memory traces. In contrast to the MCM, the TBRS model predicts dual-task costs that are directly related to the amount of time participants spend attending to the secondary processing task: the more time that is spent on this task, the greater the degree of memory decay, and the less time that is then available for redintegration processes.
1.2 Difficulties in comparing working memory models.

As previously discussed, there exists a large number of models of working memory including those detailed in the preceding pages. Models can be useful for generating hypotheses, making predictions about the outcomes of one’s own experiments and those conducted by others, and can provide a revisable framework to compare and contrast with the ideas and theories of others. However, when research questions are posed by those with specific theoretical assumptions in mind, and investigated with like-minded colleagues using procedures and analyses aimed at detecting those phenomena the researcher most expects to observe, the whole process can create a cycle that hampers true understanding. While scientific debate is valuable, it can lead to an extensive yet contradictory literature. Researchers can become entrenched in their ideas while overlooking similarities between their own theory and the theories of others. Here we discuss some potential pitfalls of focusing too narrowly on models, and the difficulties in interpreting data without bias towards one’s own theory.

Flexibility of models.

Revising theories based on new evidence is a fundamental process of science. However, when new data contradict previously held assumptions those models that have inbuilt flexibility can often incorporate these new findings or phenomena in such a way that leaves core principles of the model intact.

An acknowledged weakness of the MCM is the ‘black box’ or ‘homunculus’, the central executive (Baddeley, 1996). Baddeley and Logie (1999) described how the main focus of the research into the MCM, prior to 1999, focussed on the phonological loop and visuospatial sketchpad, and had proven useful in generating testable
1.2. Difficulties in comparing working memory models.

hypotheses and identifying phenomena specific to these components. However, the authors also acknowledged that the mechanisms of the central executive have been comparatively unexplored. The central executive was said to be responsible for the co-ordination of the slave systems, and have some involvement in other higher-order executive functions (Baddeley, 1996, 2007). Logie (2016) has suggested that the central executive may instead be an “emergent property” (pp. 12) of multiple specialised processes working in unison to suit specific task goals. However, even this approach does not avoid ‘executive function’ as an easy answer to difficult questions when interpreting surprising and/or unexpected data patterns and behavioural phenomena. Replacing the ‘homunculus’ with multiple specialised skills, strategies, and abilities may simply be replacing one box with multiple others. Such an approach can be useful in generating research questions, but those who propose simpler systems for working memory based on principles of spreading activation or shared-resources are unlikely to be satisfied with such an answer.

Another example from the MCM literature is the addition of the ‘episodic buffer’ to account for data for which domain-specific slave systems could not easily explain performance on some types of tasks (Baddeley, 2000). For example, Baddeley (2000) describes how although AS has a clear effect on memory for verbal items, presumed to be due to disruption of phonological codes, performance drops are relatively modest as participants are still able to recall a number of items. Likewise, case studies of patients with severely impaired short-term verbal memory for items presented aurally can recall longer lists if they are presented visually. Baddeley argued that this problem, and others related to the co-ordination between short- and long-term memory or other more complex working memory processes and phenomena, could be explained by a multiple component model of working memory that included a domain-general buffer or store.
1.2. Difficulties in comparing working memory models.

The episodic buffer has been a popular concept since its introduction (to date, Baddeley, 2000, has over five thousand citations). However, it could be argued to be an overly flexible solution to the problems of the prior three-component model. Baddeley (2000) acknowledged that the introduction of the episodic buffer was a significant change to the model’s framework, and in fact suggested it may be thought of as a “fractionation of the older version of the central executive” (pp. 422). Logie (2011) proposes that the episodic buffer could be interpreted as interconnectivity among existing components, evidenced by the specific deficits exhibited by AD patients in dual-tasking (Logie et al., 2004) and feature binding (Parra et al., 2009).

Even if the central executive and episodic buffer are revised or re-imagined as a collection or culmination of other executive functions, an “infinite hierarchy of . . . homunculi” (Logie, 2016, pp. 1) will never provide a satisfying end point for some. In discussing this problem and possible future directions, Baddeley and Logie (1999) stress the advantage of focusing on testable research questions and empirical studies that may detect phenomenon that may ultimately lead to an understanding of ‘executive control’.

An example of model flexibility from the TBRS/refreshing literature can be found in a paper by Vergauwe et al. (2016). This study aimed to detect serial refreshing by probing memory at different time frames and measuring response times. The hypothesis was that if lists of items are refreshed serially, then probing memory at different intervals should result in different serial positions being retrieved. Refreshing has been argued to be a serial process, with attention shifting from one item in a list to the next (Barrouillet & Camos, 2012; Cowan, 2011). The assumption that only one process could be completed at one time is a core tenet of the original TBRS model (i.e. one item being refreshing, or one distractor item being processed) (Barrouillet et al., 2004), with the resulting ‘bottleneck’ being the reason for increased forget-
Difficulties in comparing working memory models.

Across four experiments, Vergauwe et al. (2016) failed to find evidence for serial refreshing in the analysis of response times to memory probes. In discussing these results, one of the proposed reasons for the lack of effect is that refreshing can occur in parallel which goes in direct contrast to the TBRS account of refreshing. Other suggested reasons are that reaction time measures do not indicate what is in the focus of attention, or that participants were not utilising refreshing (although one experiment specifically included AS to require the use of refreshing over sub-vocal rehearsal, see Camos et al., 2009, 2011).

Interpreting data within the context of a model.

When data does not fit with a researcher’s preferred model it is often reinterpreted or re-evaluated. When this is the researcher’s own data perhaps a follow-up experiment with small tweaks to procedures is carried out that would not have been done if the original data were found to fit with the model. Equally, research findings supporting one theory can be interpreted and explained by the concepts of another model (often a symptom of the over-flexibility of models discussed above).

For example, Barrouillet et al.’s (2004) initial investigation of cognitive load included comparisons of slow and fast rates of number reading. In line with the TBRS model’s assumption of a shared attention-based resource, the effect on memory recall accuracy between low and high presentations has been argued to be evidence of a shift of attention away from maintenance of memory items. However, such an effect could equally be explained by an effect of AS since faster rate of speech should reduce participants’ ability to sub-vocally rehearse (especially experiment-paced vocalisations, see Hudjetz & Oberauer, 2007), or by interference accounts of forgetting due to the greater number of items presented in the high load condition (e.g. Oberauer & Lewandowsky, 2008; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves,
1.2. Difficulties in comparing working memory models.

2012). The data presented by Barrouillet et al. (2004) are not inconsistent with other models which would predict similar effects of the experimental manipulations.

Likewise, what Duff and Logie (2001) consider to be small dual-task costs would be considered evidence for an attentional trade-off in favour of the processing task. A problem arises due to the focus that different models place on different aspects of performance: put simply, the MCM focusses on the preservation of memory performance under dual-task conditions and as such views any successful concurrent memory and processing as evidence of separable components, even if performance is lower in dual-task than single-task conditions. In contrast, models that assume a shared-resource inevitably focus on costs to memory during dual-tasking, and tend not to provide an account for the high levels of residual performance under dual-task conditions.

Biased by design.

When researchers design an experiment, their procedures, tasks, analysis plans, etc. are often based on their own previous research as well as the research of others. When researching and developing their own theory or model, researchers’ goals may range from replicating their own previous findings, further investigation of a phenomenon important to their theory, or adapting the procedures used in a competing model’s literature to demonstrate how incompatible findings are due to some methodological characteristic of the design. Undoubtedly the iterative process of scientific discovery relies heavily on such procedures, but it can be difficult to avoid biasing one’s own research in such a way that detecting those essential phenomena is all but guaranteed. To be clear we do not suggest that such behaviour is nefarious, only that as researchers go further down a specific research path their experiments will likely follow a methodology that has been specifically developed to detect the patterns of
1.2. Difficulties in comparing working memory models.

An example from the TBRS research can be found when contrasting experiments investigating the effect of processing task load (cognitive load) on memory accuracy with experiments investigating the effect of memory load on processing performance. As previously summarised, TBRS theory states that refreshing of memory items requires attention, and that the more time that attention is diverted away from refreshing memory traces the more these traces decay. As such, TBRS methodology invariably includes stringent performance criteria for concurrent processing tasks: if researchers are not certain that participants are focusing on processing tasks they can not be confident that attention has been successfully diverted. This leads to a proportion of participants being removed from the original samples due to ‘poor’ processing accuracy (e.g. Camos et al., 2009: ~1 – 5% of participants removed from each experiment; Vergauwe, Barrouillet, & Camos, 2009: ~6 – 8% from each experiment). Conversely, when investigating the effect of memory load on processing performance, Vergauwe et al. (2014) removed a number of participants who failed to reach an accuracy criterion for the memory task. Vergauwe et al. excluded participants from each of the seven reported experiments, with the total proportion of participants excluded across all experiments being 18.2%. The authors describe a ‘skimming procedure’ in which only blocks for which two thirds of participants achieved 100% accuracy in 2/6 trials at a given list length were analysed. This means that of all the participants that took part in the seven experiments, 22.4% were excluded from the analyses reported in the paper. Of all the trials from these remaining participants, 61.9% were included in the final analyses. While the authors describe the reasoning behind their skimming procedure, it is difficult to assess the findings when such extensive data cleaning has been carried out. The generalisability and replicability of these findings are also severely impacted as any replication
1.2. Difficulties in comparing working memory models.

attempt would either need to be bound by the same time-consuming process of collecting data that will later be excluded during the skimming procedure, or forgo the skimming and have any failure to replicate dismissed as a difference in experimental procedure.

These exclusion criteria make sense if one assumes cognitive load is a true effect, but it assumes that if a resource trade-off exists it does not vary by individual. If different participants attribute importance either to the memory or processing task then, for example, removing those who perform poorly on the processing task biases the sample towards individuals who focus on the processing task and potentially exaggerating costs to memory performance. Also, the drive to ensure that participants attend to the processing task to a sufficient degree to elicit a cognitive load effect on memory span means that extensive practice is often given to participants before the experimental conditions (e.g. Portrat et al., 2008), effectively training participants to focus on the processing task. These biases result in a sample that is predisposed to demonstrate specific effects that is then reduced to a smaller sample of participants who most strongly demonstrate these effects.
1.3 Summary of the presented research.

The presented thesis reports experiments that aimed to investigate the effects of sub-task load on both memory and processing performance during dual-tasking. As previously discussed, the Multiple Component and TBRS models have been used to generate hypotheses as both these models assume decay to be the main source of forgetting in short term memory. Based on Logie’s (2011) suggestion that shared-resource effects may be observed once the capacity of a memory store has been exceeded, and Camos et al.’s (2009, 2011) findings that both sub-vocal rehearsal and attentional refreshing can be recruited to suit specific task conditions, we aimed to investigate at what stage participants tend towards one maintenance mechanism over the other. Our hypotheses were based on the assumption that people tend towards low-demand methods of rehearsal when possible (e.g. for verbal memory participants would rely on sub-vocal rehearsal), but support specialised memory stores with attention-based refreshing once the demands of the task begin to exceed their abilities. The findings that memory load only affects concurrent tasks for longer lists (Baddeley & Hitch, 1974), that concurrent processing reaction time is only affected for longer lists or when verbal memory tasks are performed under AS (Vergauwe et al., 2014), and that participants can automatically or purposefully switch between articulatory and attention-based rehearsal methods (Camos et al., 2009, 2011), all suggest that participants can provide data supporting multiple-component and shared-resource theories of working memory.

Our initial investigations, reported in Chapter 2, focussed on comparing single-task performance in memory and processing tasks to performance under dual-task conditions. Based on our observation that a number of TBRS studies report the exclusion of participants based on poor performance on the processing component of a dual-task, we aimed to ensure that participants were given tasks set at demand
1.3. Summary of the presented research.

levels based on their own measured ability. For example, when remeasuring memory span under dual-task, Doherty and Logie (2016) adjusted the demand of the processing task was manipulated according to each participant’s single-task processing span. This meant that ‘low’ and ‘high’ cognitive load conditions were an accurate description of the demand experienced by each participant. The experiments reported in Chapter 2 revealed that while verbal memory span was unaffected by concurrent spatial processing there was a cost to dual-task processing accuracy observed when memory load was set above participants’ span. The opposite pattern was observed for a visual memory task paired with a spatial processing task: an effect of processing task load was observed on memory span, but this effect was only present once the processing task demand was set beyond participants’ single-task capacities. We argue that participants are able to co-ordinate memory and processing tasks successfully, but that dual-task performance suffers once sub-task demands begin to exceed participants’ abilities within each cognitive resource that is used to support performance.

In Chapter 2 dual-task effects on memory were observed when a visual memory task was paired with spatial processing. Chapter 3 investigated the effect of manipulating both memory and processing load within the same experiment on memory and processing accuracy. When paired with a concurrent spatial processing task, visual memory was affected by concurrent load only when both memory and processing tasks were set above participants’ individual span. The effect was not observed when the processing task was verbal. No effects of memory load on verbal or spatial processing accuracy was observed in either experiment.

While the results from Chapter 3 supported our hypothesis regarding above-span dual-task effects, the visual task utilised in Experiments 3 and 4 did not lend itself well to ‘span-1’ and ‘span+1’ load manipulations. For this reason we switched to a
verbal memory task for Experiments 5-9. In Chapter 4, Experiment 5 revealed an effect of concurrent processing load on memory accuracy only when the processing task was set above participants’ span. The same pattern was also found for processing accuracy.

Upon establishing the above-span load effect on memory and processing accuracy which we argue to be due to a switch from low-demand sub-vocal articulation to attentionally demanding maintenance processes, we turned our focus to identifying the circumstances under which participants make this switch in rehearsal method. Chapter 5 compared verbal memory and verbal processing dual-task performance across three experiments. Experiment 6 revealed a similar pattern of memory and processing performance observed in Experiment 5. Experiments 7 and 8 featured small changes to the procedure of Experiment 6 aimed at predisposing participants to either sub-vocal rehearsal or attention-based maintenance. The results of these experiments revealed that when participants rely on sub-vocal rehearsal their dual-task memory performance is unaffected by concurrent processing task load. When task constraints favour the use of attention-based maintenance dual-task performance is severely affected by the demand of the concurrent verbal processing task.

The final experimental chapter, Chapter 6, investigated the effect of manipulating task priority. Although we never instructed participants to prioritise either task (asking that participants attempt each task to the best of their abilities), we were curious as to how instructing participants to focus on one task or the other, or giving them no instruction as to the priority of tasks, affected performance. It was found that when participants were instructed to give one task priority over another then performance on the non-priority task dropped considerably while no benefit to the priority task was observed. Giving participants no instructions or instructing them to focus on both tasks equally resulted in the best overall dual-task performance.
Chapter 2

Initial Investigation of Titrated Demand
Being the seminal study investigating the TBRS theory of working memory, Barrouillet et al.’s (2004) paper has influenced the methodology of the TBRS literature, including the possibility of ‘over-loading’ working memory components due to an insensitivity to participants’ individual ability. As discussed in the previous chapter, a number of subsequent TBRS papers explicitly describe the exclusion of participants or individual trials from analyses due to high error rates (e.g. Barrouillet et al., 2007; Camos et al., 2009; Vergauwe et al., 2009, 2014), suggesting that the task demands were beyond the capacity of the working memory resources of some participants. The tasks reported in the TBRS studies may therefore provide a good measure of maximum operating capacity of working memory when the overall task demands exceed the participants’ working memory capacity. At these very high cognitive loads, data patterns could give the impression of performance being constrained by a single, limited capacity system while being insensitive to the contribution of discrete, specialised components to that maximum operating capacity.

Compared to the numerous demonstrations of the ‘cognitive load’ effect by Barrouillet and colleagues, previous research has shown that titrating task demand results in very small dual-task costs. In two experiments Cocchini, Logie, Della Sala, MacPherson, and Baddeley (2002) tested dual-task visual and verbal memory performance with a concurrent processing task (spatial tracking), and with articulatory suppression. Task demands were adjusted according to each participants’ single-task ability. Cocchini et al. found no dual-task effect of combining memory and processing tasks on delayed recall or on processing accuracy. The authors noted that articulatory suppression has a much larger effect on verbal memory than the addition of a processing task, suggesting that memory accuracy during dual-tasking has more to do with the availability of specialised verbal rehearsal methods than with a general attention resource.
Logie et al.’s (2004) study of dual-tasking in Alzheimer’s Disease (AD) patients also titrated dual-tasks based on single-task performance. Comparing younger and older adults’ performance with patients’, Logie et al. found that while the latter group showed no difference in digit spans compared to the former groups, and no difference in tracking speed compared to older adults. However, patients’ dual-task performance was considerably reduced compared to both younger and older adults. The authors note that despite reduced overall dual-task performance in patients, increasing the demand of either the memory or processing task did not affect performance on the other task.

Researchers are often most interested in the overall capacity limit of the system and so the potential pitfalls of failing to titrate task demand do not pose a problem for them. However, Logie (2011) noted that the multiple-component framework for working memory is less concerned with this emergent overall capacity, and rather more concerned with the underlying cognitive mechanisms that contribute to this overall capacity. For example, individual differences in working memory capacity could be explained by both the capacity of components working in concert to support overall performance levels, and by the assumption that additional components are recruited to provide support for task performance when overall task difficulty increases beyond the capacity of individual components.

In a review of simple and complex span literature, Unsworth and Engle (2007) found that simple span (memory without concurrent processing) predicted higher order cognitive abilities to the same extent as complex span (memory with concurrent processing) as long as performance was measured using long lists: the magnitude of the correlations between fluid intelligence and performance on simple span and complex span converge on a similar value at longer list lengths for the simple-span task. Reviewing data from multiple papers, the authors note that simple span performance
is more reliant on phonological processes and so is more disrupted by articulatory suppression, phonological similarity among items in the list, and by lists comprised of longer words compared to lists of shorter words. Unsworth and Engle note that complex span most likely relies on phonological processes in addition to the processes that correlate with higher order cognition. They propose that simple span performance on shorter lists depends on ‘Primary Memory’ (PM), and that as list lengths increase items are displaced and stored in ‘Secondary Memory’ (SM). In complex span tasks memory items are displaced from PM by the concurrent processing task, and are retained in SM. The correlation between long-list simple span tasks and fluid intelligence, and between complex span tasks and fluid intelligence, are therefore proposed to be driven by individual ability in retrieving items from SM. It is also interesting to note the implication that complex span tasks, also referred to as working memory span tasks, might be measuring ease of retrieval from secondary memory, or long-term memory, and therefore might not actually be measuring the capacity of working memory. In sum, Unsworth and Engle’s results suggest that when demands on memory in simple span exceed the capacity of temporary verbal memory, then other resources in the cognitive system contribute to overall performance. This has the implication that with high memory loads, memory performance may be driven by retrieval from a verbal representation in long-term memory, that might be disrupted by attentional refreshing, whereas low memory loads may rely on a phonological representation in temporary verbal memory that is disrupted by articulatory suppression.

In previous research we investigated whether titrating secondary processing task demand according to participants' individually measured abilities reduced dual-task
costs on memory performance. Doherty and Logie (2016)\textsuperscript{1} combined a verbal memory task (digit span) with a concurrent spatial processing task. The spatial processing task required participants to judge as quickly and accurately as possible whether successive boxes were placed in the top or bottom half of the computer monitor. A dual-task combination of verbal memory storage and spatial processing was chosen to allow interpretation of any effects in terms of attentional trade-off rather than due to domain-specific interference that might arise from combining verbal memory with verbal processing. Memory span was calculated in single- and dual-task conditions, with dual-task conditions having a secondary processing task set at different loads. Each processing task load increase resulted in a higher ‘cognitive load’ as defined by Barrouillet et al. (2004, 2007). Importantly, processing task demand was set according to each participants’ individually measured ability. Therefore the difference between ‘low’ and ‘high’ demand dual-task conditions was titrated for each participant, with dual-task memory span being measured under four load conditions: ‘Span -1’, ‘At Span’, ‘Span +1’, and ‘Span +2’. The procedures for the single-task span conditions, and the dual-task span conditions are shown in Figure 2.1.

Doherty and Logie (2016) found evidence for a verbal memory store and rehearsal mechanism which operates independently of concurrent spatial processing. Specifically, participants’ verbal memory spans were not significantly affected by the introduction of the spatial processing task or with each subsequent increase in processing load between the ‘Span -1’ and ‘Span +2’ conditions (see Figure 2.2). In contrast to the verbal memory data, spatial processing accuracy was affected by the demand of the memory task: participants’ processing accuracy was lower when their memory was ‘pushed’ above span (see Figure 2.3). This supports Logie’s (2011) hy-

\textsuperscript{1}Data for Experiment 1 in Doherty and Logie (2016) were submitted as part of a Master of Science by Research dissertation and so are only summarised here. Experiment 2 from the same paper was conducted during the current programme of research and so is reported in full in the following section, and is labelled ‘Experiment 1’.
Figure 2.1: Span and dual-task procedures from Doherty and Logie (2016). Memory (top left) and processing (top right) spans were collected for each participant and used to titrate the dual-task conditions (bottom). Dual-task memory spans were then remeasured with the processing task set at ‘Span -1’, ‘At Span’, ‘Span +1’, and ‘Span +2’.

The hypothesis regarding recruitment of domain-general resources when working memory components are under a load that exceeds their capacity. The effect of memory load on spatial processing accuracy was interpreted as the effect of the reallocation of a processing resource once the phonological loop’s capacity is exceeded. It could, for example, reflect attempts to use a visuo-spatial strategy to retain some of the memory items in support of an overloaded phonological loop. A number of studies have shown the use of visuo-spatial codes and other codes (e.g. semantic) to retain sequences of verbal material (e.g. Borst et al., 2012; Logie et al., 1996, 2000; Logie, Saito, Morita, Varma, & Norris, 2016; Saito et al., 2008). It is possible that recoding
verbal memory items in a visual or other code is an attentionally demanding process that is susceptible to disruption when attention is required for some ongoing processing task.

Within the context of a shared-resource approach to working memory the results of Doherty and Logie’s (2016) first experiment may be interpreted as evidence of a general purpose resource facilitating both memory and processing tasks, with the ‘primary’ memory task taking precedence over the ‘secondary’ processing task, with trade-off in accuracy in line with the effect on RTs observed by Vergauwe et al. (2014). Experiment 1 reported here investigated whether the effect on processing accuracy is limited to when memory load is set above span (evidence for separable resources when memory load is set at span level or below), or whether processing accuracy is
improved at below-span memory load levels (evidence for a constant shared-resource trade-off). Following on from this, Experiment 2 paired a visual working memory task with the spatial processing task to test the distinction between memory and processing resources, and whether both resources can be allocated to support the other. Based on the concepts of a phonological loop and visuospatial sketchpad, we assume a domain-specific verbal and visual short-term memory components of working memory. Once the capacity of a memory store is reached participants can support memory performance by drawing on other cognitive resources. Whether this memory support involves increased reliance on strategies (Logie et al., 1996), the use of visual codes for verbal materials (e.g. Logie, Saito, et al., 2016; Saito et
al., 2008), storage and retrieval of items stored in secondary memory (Unsworth & Engle, 2006, 2007), or some other process such as ‘refreshing, we would argue that such a process requires attention above and beyond what is required for at-span or below-span lists.
2.1 Experiment 1: Spatial processing span & verbal memory

Introduction

Doherty and Logie (2016) measured memory span under single- and dual-task conditions with processing load set according to participants’ single-task processing spans, and found that while memory span was unaffected by processing load there was a significant effect of memory load on processing accuracy. We theorised that this effect of memory load was due to participants diverting resources from constantly updating information in the spatial processing task in order to support an ‘over-loaded’ phonological loop. Memory load was not directly manipulated, and instead relied on an analysis of processing accuracy at the level participants failed the memory component of the dual-task conditions and at the highest level at which they succeeded. The follow-up experiment reported here aimed to directly compare spatial processing performance with varying levels of concurrent verbal memory load.

We predict a marked drop in processing accuracy as memory load is increased above participants’ span and attentional resources are recruited to support memory performance. Since memory resources are assumed to be specialised, we do not expect an effect of ‘above span’ processing load on memory accuracy as we observed in the first experiment reported in Doherty and Logie (2016).
Method

Participants and Apparatus

Participants were recruited from the University of Edinburgh Psychology Department’s Participant Pool for first year undergraduate Psychology students. Twenty-four participants took part in the experiment in exchange for course credit (4 male and 20 female, mean age = 19.0, range = 18-29). Data were collected using 36cm×27cm displays set at 800 × 600 pixel resolution and 60Hz refresh rate situated approximately 50cm from participants who responded via the keyboard. The experiment was programmed in the E-Prime 2.0® environment.

Procedure

Each participant completed six conditions in total: single-task memory and processing span conditions, and four combined memory and processing dual-task span conditions. The single-task conditions were counterbalanced yet always preceded the dual-task conditions. The dual-task conditions were fully counterbalanced, resulting in 24 counterbalanced conditions.

Each participant’s memory ability was measured using a span procedure in which they were required to recall number sequences of increasing length. Numbers appeared in the centre of the screen consecutively for 1000ms each and were followed by a 6000ms fixation cross (+). Following this retention interval, participants were asked to enter the numbers in order into an on-screen text box using the numeric row on the keyboard. Each ‘level’ (e.g. four items to remember, five items to remember, ... etc.) featured five randomly generated lists, and participants were required to accurately recall at least 4/5 lists to proceed to the next level. This continued until participants were unable to reach this criterion, at which point their memory span was calculated as the average length of the last five correctly recalled lists. For
example, if a participant correctly recalled 4/5 five-item lists, and 1/5 six-item lists their memory span would be calculated as 5.2. This 4/5 criterion was chosen as a cut off at which participants begin to perform below ceiling and so would provide an accurate sensitive measure of memory capacity, and also to provide some parity with the processing task described below. The strictness of the criterion also ensured that the difficulty of the memory task would be set at an appropriate level for the introduction of a concurrent processing task.

Participants’ spatial processing ability was also measured using a span procedure in which they were instructed to judge whether successive ‘boxes’ were situated in the top or bottom half of the screen, and answer via a key-press. The location of boxes deviated randomly within a ±15 to ±20 pixel range vertically, and ±150 pixels horizontally (though no two consecutive processing stimuli could appear within 130 pixels of each other). This equates to an average vertical visual angle of 1.8 degrees between the ‘up’ and ‘down’ stimulus locations. The task began with the presentation of four boxes, one after the other, over the course of 5000ms, with each box remaining on-screen for 25% of the total 5000ms. The number of boxes increased in the same way as the digits in the memory task, although the length of time in which all the stimuli were presented remained the same. This meant that with each increase in ‘level’ the amount of time available to process successive boxes decreased. Participants’ accuracy was calculated at the end of each level, and only those with an overall accuracy ≥ 80% were permitted to continue on to the next level. The last level at which participants reached the 80% accuracy level was recorded as their spatial processing span. Accuracy was calculated as the average of all responses for a block of trials. This 80% criterion was set according to the standard ‘cut-off’ reported in the TBRS literature (e.g. Barrouillet et al., 2007; Vergauwe et al., 2009; Vergauwe, Barrouillet, & Camos, 2010). Performance below this level is deemed
insufficient to disrupt concurrent memory storage due to unreliable cognitive load. Utilizing this cut-off in our own experiments allows some comparison with previous research whilst providing a sensitive measure of verbal processing similar to our 4/5 memory span procedure.

The dual-task conditions combined the memory and processing tasks, and were identical to the single-task memory span condition except that following the presentation of the last memory item there was a 1000ms fixation followed by the spatial processing task for 5000ms. Upon completion of the processing task participants entered the previously presented numbers in the same way as in the single-task condition. Participants were instructed to perform both tasks as accurately as possible and neither task was labelled or implied to be the primary/secondary task. Participants completed four dual-task conditions, each with the memory task set at different load levels based on each participant’s individually measured verbal memory span. For example, a participant who had reached a verbal memory span level with lists of 5 items would complete the four dual-task conditions with the memory task set at four (‘Span-1’), five (‘Span=’), six (‘Span+1’), and seven (Span+2) items. The ‘cut-off’ for dual-task processing span was the same as in the single-task condition.
2.1. Experiment 1: Spatial processing span & verbal memory

Results

A note on analyses. We report both p values and Bayes Factors for each analysis. The use of frequentist statistics facilitates comparison with previous literature and are interpretable by a wide audience, whilst Bayes Factors benefit from their ability to contrast two hypotheses which may or may not include a null hypothesis.

Bayes Factors were calculated using the BayesFactor package (Rouder, Morey, and Province, 2012) in R (R Core Team, 2013). Priors for fixed effects were set at the default level of ‘medium’ ($\sqrt{2}/2$). ‘Null’ hypotheses refer to intercept-only models.

Spatial Processing

The mean single-task processing span for participants was 8.13 (SD = 1.12). Spatial processing was analysed by comparing the accuracy from the highest common ‘span level’ of the single- and dual-task conditions. For example, if a participant had reached ‘eight boxes/5000ms’ in the single-task condition, and ‘six boxes’, ‘seven boxes’, ‘six boxes’, and ‘five boxes’ in each of the dual-task conditions, the accuracy scores (% correct) from each condition’s ‘five boxes’ level would be compared. Conducting the analysis in this way allowed us to maintain a methodology near identical to Doherty and Logie’s (2016) investigation of memory span, yet permitted a more precise comparison of processing accuracy scores rather than maximum span level reached under each condition. The mean highest common span level was 5.92 (SD = 1.72).

Scores were compared via a repeated-measures ANOVA and revealed a significant main effect of memory load on spatial processing accuracy ($F[4, 92] = 8.325, \eta_p^2 = 0.266, p < 0.001$) (see Figure 2.4). Repeated-measures contrasts revealed no significant differences in accuracy between each successive condition (all $p > 0.243$) except ‘Span+1’ and ‘Span+2’ conditions ($F[1, 23] = 7.60, \eta_p^2 = 0.248, p = 0.011$).
These results reveal that as the memory load increased performance on the concurrent spatial processing task decreased, with the largest effect appearing between the ‘Span+1’ and ‘Span+2’ conditions. Figure 2.4 strongly supports the conclusion that there is a lack of an effect of memory load between the ‘Single-Task’ and ‘Span-1’ conditions ($BF = 4.65 \pm 0.03\%$ against a difference between conditions), in line with the hypothesis that the recruitment of additional resources only occurs once the verbal memory store’s capacity is exceeded.

We also analysed reaction times to investigate whether we replicated Vergauwe et al.’s (2014) findings. It is important to note that Vergauwe et al.’s processing task was participant-paced whereas our task was experiment-paced, and so we had to take steps to avoid artefacts in our data due to non-responses. In calculating participants’
Figure 2.5: Experiment 1 - Mean memory accuracy (with standard errors) when processing load was ‘at span’ and ‘above span’, shown across all dual-task conditions.

Mean reaction time for each memory load condition, we removed any non-response trials as well as trials in which reaction time was < 250ms. An analyses of these data revealed no effect of memory load on reaction time: $F(3, 69) = 0.32, \eta^2_p = 0.013, p = 0.811$. A Bayesian analysis found ~12 times more evidence for the null model ($BF = 12.50 \pm 0.45\%$ against an effect of memory load).

**Processing Load × Memory Load Analysis of Memory Accuracy**

Mean single-task memory span was 6.18 (SD = .86). We compared performance in trials for the most demanding level of each dual-task condition with the lower load trials from the preceding block. Since spatial processing performance was the critical factor in passing each span level, these analyses aimed to compare concurrent
memory storage (measured as a percentage of total memory items recalled in position in a block of trials) when participants’ spatial processing was operating at span and when it was operating above span. In Doherty and Logie’s (2016) investigation of verbal memory span the analysis indicated that attentional resources were being diverted from the spatial task in order to support memory performance. A 2(processing load: ‘At Span’ vs. ‘Above Span’) 4(memory load: ‘Span -1 → Span +2’) repeated-measures ANOVA revealed a significant effect of memory load on memory accuracy ($F[3, 69] = 56.362, \eta_p^2 = 0.710, p < 0.001$) and a significant effect of processing load ($F[1, 23] = 5.087, \eta_p^2 = 0.181, p = 0.034$), but no significant interaction ($F[3, 69] = 0.618, \eta_p^2 = 0.026, p = 0.606$) (see Figure 2.5). A Bayesian analysis revealed that there was around 9 times more evidence for main effects only compared to main effects with an interaction ($BF = 9.54 \pm 0.45\%$). However, the Bayesian analysis also revealed little evidence for an effect of processing task load on memory performance, with the model containing ‘memory load only’ being preferred over all other models, and being supported by a Bayes factor of $1.37 \pm 0.71\%$ over the model with the next largest Bayes factor, the ‘memory load + processing load’ model.

It is important to note that although participants’ memory accuracy decreases with increasing memory loads, performance is still high (remaining above 70% in the ‘Span +1’ condition). Relating this back to our hypothesis that storage draws upon additional resources once memory capacity is exceeded, the fact that memory performance does not drop to very low or chance levels in Figure 2.5 supports the interpretation that participants are recruiting the similar resources as those responsible for the processing task (resulting in the drop in processing accuracy seen in Figure 2.4) which enables them to maintain memory performance using a memory-specific resource under demanding dual-task conditions.
Discussion

Experiment 1 was successful in demonstrating the effect of diverting resources away from spatial processing to support increasing memory demands. As the demand of the memory task increased, participants appeared to rely more on resources also involved in the on-line processing of spatial stimuli.

Our reaction time analysis did not replicate Vergauwe et al.’s (2014) findings, however this is likely due to both the aforementioned differences between our procedures and the fact that our participants were not doing the tasks under AS. It is notable that Vergauwe et al.’s largest effects were in the articulatory AS conditions, with smaller effects in the non-suppression condition. It is possible that Vergauwe et al.’s participants were intentionally answering more slowly when under high memory load in an attempt to maintain performance through attentional refreshing or the use of some other mechanism, resulting in larger changes in reaction times than possible under our procedure.

The memory accuracy analysis revealed a small effect of processing task load on memory performance, whilst the Bayesian analysis provided very weak (or ‘anecdotal’, Wetzels & Wagenmakers, 2012) evidence against an effect of processing load. Therefore, if there is any processing load effect on memory accuracy it appears to be smaller than the effect of memory load on processing accuracy observed in this experiment and in Doherty and Logie (2016).

In response to Portrat et al. (2008), Lewandowsky and Oberauer (2009) found that the number of errors participants made on a concurrent processing task were a better predictor of dual-task memory performance than the cognitive load of the task. Portrat et al. measured participants’ complex span with a concurrent spatial processing task similar to the one reported here. The demand of the processing task was manipulated by increasing/decreasing the discriminability between the two spa-
2.1. Experiment 1: Spatial processing span & verbal memory

tial locations in which the stimuli appeared. The authors found that memory spans were lower when the spatial locations were closer together compared to when the locations were easily discriminable. However, Lewandowsky and Oberauer argued that since the TBRS model assumes that the effect of cognitive load is dependent on the total time that attention is captured by the distractor task then any additional diversion of attention should also affect performance. Since increased cognitive load equates to an increase in task difficulty, higher cognitive load tasks will result in higher error rates. This was the case in Portrat et al., so Lewandowsky and Oberauer reasoned that since errors are known to capture attention as the error is processed (evident in the slower reaction times for trials immediately following an error: see Laming, 1979; Jentzsch & Dudschig, 2009), then the reported effect of cognitive load could in fact be an effect of error processing preventing refreshing of memory items. Lewandowsky and Oberauer confirmed that post-error slowing of RTs are observed in the spatial judgement task utilised by Portrat et al., with a reanalysis of Portrat et al.’s data confirming that the number of errors made by participants’ were a better predictor of memory performance than the cognitive load manipulation. Lewandowsky and Oberauer argued that the small drops in memory performance observed by Portrat et al. were due to increased error processing, and that the time spent on processing items could not be the sole cause of memory decay.

It is therefore possible that the small effect of above-span spatial processing load on memory performance was due to the increased error rate in this condition. Since the ability to co-ordinate two tasks has been argued to be a specific ability (Logie et al., 2004), and that small dual-task costs to memory have been observed with no other cost of increasing concurrent task load (Duff & Logie, 1999, 2001; Logie & Duff, 2007), it is possible that processing errors has a disruptive effect on participants’ ability to co-ordinate storage and processing and that when error rates
are sufficiently low then both can be performed in parallel.

Doherty and Logie’s (2016) investigation of dual-task verbal memory span found no effect of concurrent task load but also no dual-task cost to span. Experiment 2 investigated whether pairing a visual memory task with a spatial processing task would result in greater interference effects due to both tasks being visuospatial in nature.
2.2 Experiment 2: Visual memory span & spatial processing

Introduction

Doherty and Logie (2016) demonstrated that adjusting the demand of a secondary spatial task according to individual ability results in no reduction in memory span, while Experiment 1 found that processing performance drops as participants’ memory load is ‘pushed’ above span. We argue that the lack of effect on memory and the effect on processing are due to separable memory resources being supplemented by attention. However, the MCM would predict domain-specific interference, in particular that temporary visual memory performance should be reduced when combined with a concurrent visuospatial processing task, even if the task demands are adjusted according to the individual participant spans for memory and for processing. A possible confound could be that the results from Doherty and Logie’s (2016) investigation of memory span were due to lack of attentional demand of the secondary task. For example, if our measures of individual span were underestimates of the genuine maximum capacities of each participant it is possible that the cognitive load levels resulting from the ‘Span -1’ → ‘Span+2’ conditions were insufficient to elicit a measurable effect on concurrent memory performance. If this were the case, then we would expect that using this same procedure but combining memory and processing tasks within the visuospatial domain should also lead to a lack of disruption of memory performance as a result of processing load.

While some studies have reported that visual and spatial tasks do not interfere with one another (e.g. Darling, Della Sala, & Logie, 2007; Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999), others demonstrate interference between spatial and visual tasks (e.g. Brown & Wesley, 2013). The stimuli for our memory and processing tasks were designed to be visually similar, so whilst evidence exists for the separation
of visual and spatial processes in working memory we would still expect a larger interference effect for visual memory with a spatial processing task than for verbal memory in Experiment 1 and in (Doherty & Logie, 2016).

Experiment 2 therefore aimed to establish whether we observe interference between visual memory and concurrent spatial processing in a titrated, cognitive load manipulation paradigm. Experiment 2 also tested the hypothesis that memory resources cannot be used to support processing performance by utilising tasks within the same domain to maximise any chance of a bi-directional trade-off.
Method

The design of Experiment 2 conformed almost exactly to that of Experiment 1: single-task memory and spatial processing scores were recorded and compared to performance in dual-task conditions in a within-participants design. The only differences between the design of Experiments 1 and 2 was the substitution of a visual pattern task for the previous verbal memory task and that memory span was re-measured under dual-task conditions rather than processing span. Participants were recruited through the University of Edinburgh Student and Graduate Employment (SAGE) Career Service and were paid an honorarium in return for their participation (n = 24 [5 male, 19 female], mean age = 20.3, range = 18-28).

Visual Memory Span Stimuli. Stimuli for the memory span condition were presented in the centre of the computer screen and consisted of a series of grids comprising square boxes (18mm×18mm) filled in black or white. Randomly generated placement of black and white boxes created patterns similar to those featured in Logie and Pearson’s (1997) investigation of visual memory span in children (sample stimuli for each memory load level can be found in Appendix A). Participants were presented with a patterned grid which remained in the centre of the screen for 500ms × the number of memory items (i.e. number of black squares shown), and was followed by a 6000ms fixation cross. Following this 6000ms delay participants were presented with a second grid with only white squares and were asked to ‘click’ the squares they remembered being black using the computer mouse. As with Experiment 1, they were required to recall 4/5 trials with 100% accuracy in order to move on to the next level. Participants completed five trials at each level of grid complexity (i.e. grids of four boxes, grids of six boxes, etc.) and their span was calculated in the same way as verbal memory span in Experiment 1.
2.2. Experiment 2: Visual memory span & spatial processing

Results

Visual Memory Span

Participants’ mean single-task visual memory span was 9.66 (SD = 1.37). A repeated-measures ANOVA revealed a significant main effect of processing load ($F[4,92] = 60.11, \eta_p^2 = 0.723, p < 0.001, BF = 1.89 \times 10^{22} \pm 1.23\%$), a significant drop in visual memory performance between single-task visual memory span and the ‘Span -1’ condition ($F[1,23] = 94.830, \eta_p^2 = 0.805, p < 0.001, BF = 8.9 \times 10^{6} \pm 0.0\%$), and a significant drop between ‘Span +1’ and ‘Span +2’ conditions ($F[1,23] = 6.895, \eta_p^2 = 0.231, p = 0.015, BF = 3.43 \pm 0.0\%$). No significant differences were observed in visual memory performance between ‘Span -1’ and ‘Span =’ conditions, or ‘Span =’ and ‘Span +1’ conditions (both $p > 0.3, BFs = 4.16 \pm 0.0\%$ and 2.90 $\pm 0.0\%$ against an effect) (see Figure 2.6).

Memory Load × Cognitive Load Analysis of Processing Accuracy

Mean processing span was 7.33 (SD = 1.37). As with Experiment 1, the effect of memory load and processing load on participants’ processing accuracy was analysed via a 2(memory load: ‘At Span’ vs. ‘Above Span’) × 4(processing load: ‘Span -1’ → ‘Span+2’) repeated-measures ANOVA. The analysis revealed a significant main effect of processing load ($F[3,69] = 13.834, \eta_p^2 = 0.376, p < .001$), but no effect of memory load ($F[1,23] = 2.08, \eta_p^2 = 0.083, p = 0.163$) and no interaction ($F[3,69] = 2.082\eta_p^2 = 0.083, p = 0.111$) (see Figure 2.7). A Bayesian analysis revealed that the main effects only model had the highest Bayes factor, and was preferred over the model containing an interaction by a factor of 2.31 $\pm 0.38\%$. The lack of effect of memory load reveals that participants’ spatial processing accuracy was not affected by visual memory load as it had been by verbal memory load in Experiment 1, and in Doherty and Logie’s (2016) investigation of dual-task verbal memory span.
2.2. Experiment 2: Visual memory span & spatial processing

Figure 2.6: Experiment 2 - Mean memory span (with standard errors) in single- and dual-task conditions.
2.2. Experiment 2: Visual memory span & spatial processing

Figure 2.7: Experiment 2 - Mean processing accuracy (with standard errors) when memory load was ‘at span’ and ‘above span’, shown across all dual-task conditions.
2.2. Experiment 2: Visual memory span & spatial processing

Discussion

The main finding in Experiment 2 that visual memory was impaired by concurrent spatial processing presents a stark contrast to the findings of Doherty and Logie (2016) regarding verbal memory span: the significant effect of secondary task demand on visual memory provides evidence for an interference effect specific to visuospatial tasks. Relating to multiple-component theory, this dissociation in memory performance suggests modality-specific retention of memory traces, with spatial processing affecting visual memory due to domain-specific interference. If participants were using a shared resource or component for both types of memory task in the single- and dual-task conditions, it would be expected that the introduction of a secondary task in the latter condition would lead to an impairment in combined task ability in both visual and verbal memory conditions. Experiment 2 demonstrates interference between visuospatial memory and processing, supporting the existence of domain-specific interference, and by extension the existence of specific visuospatial functions within the working memory system.

An important feature of the visual memory data is the lack of effect between the ‘Span -1’, ‘Span =’, and ‘Span +1’ conditions. This pattern of results suggests that participants’ visual memory scores are less impaired when the secondary spatial processing task is set below their single-task ability (see Figure 2.6, page 63), but when the processing component in the dual-task conditions is set at or above a participants’ single-task span they are unable to supplement their memory performance due to the high demand of the processing task.

Also, the analysis of spatial processing data revealed no effect of concurrent memory load (see Figure 2.7, page 64). In Doherty and Logie (2016) and in Experiment 1, participants appeared to supplement their verbal memory performance with a domain-general resource once their phonological loop was ‘pushed’ beyond capac-
ity. The fact that this pattern was not observed in Experiment 2 suggests that participants were already utilising all available resources when co-ordinating a visual memory task with concurrent spatial processing, and as such once their visual memory capacity is exceeded they are unable to support their performance through recruitment of additional resources. The visual memory and processing analyses suggest that when both memory and processing tasks involve stimuli from the same domain the processing task takes precedence. It is possible that maintaining visual memory items in the face of spatial interference places considerable demands on the resources within visuospatial working memory, and that the introduction of a secondary processing task results in a significantly larger domain-specific dual-task cost compared to tasks where memory and processing demands draw on separate systems.
2.3 General Discussion of Doherty & Logie (2016), and Experiments 1 & 2

We aimed to test the hypothesis that working memory comprises multiple components, each of which has its own capacity, and that when the capacity of a particular component is exceeded then performance can be supplemented by automatic or intentional recruitment of other resources, for example through the use of visual codes for verbal material (e.g. Logie et al., 2000; Saito et al., 2008), the spontaneous use of some attention-demanding cognitive strategy other than sub-vocal rehearsal (e.g. Logie et al., 1996), attentional refreshing (e.g. Camos et al., 2009, 2011), or the involvement of retrieval of memory traces from activated secondary or long-term memory (Unsworth & Engle, 2006, 2007).

Our previous research revealed no significant effect of increasing processing demand on concurrent retention and subsequent recall of memory items set at span for each participant (Doherty & Logie, 2016, see Figure 2.2 on page 45). This provides further support (Baddeley, 1992; Camos et al., 2009) for a separation of temporary verbal memory storage from concurrent spatial processing. The analysis of processing accuracy revealed a significant drop in spatial processing performance once participants were ‘pushed’ beyond their verbal memory capacity. We interpret this as an indication of a reallocation of attention from the processing task in support of the increased demand of the memory task: additional resources are recruited to support performance as the capacity of the verbal store is exceeded.

This reallocation of attention is further supported in Experiment 1, where the significant main effect of memory load on processing performance was largest between the two highest memory load conditions (‘Span +1’ and ‘Span +2’). The fact that there was no difference between the single-task condition and the ‘Span -1’ dual-
2.3. General Discussion of Doherty & Logie (2016), and Experiments 1 & 2

Task condition (see Figure 2.4 on page 53) supports the hypothesis that attention reallocation only occurs once the verbal memory store is at or above capacity and not before.

Another interpretation could be that rehearsal requires access to a general attention resource, but that it is only once tasks become very demanding that dual-task effects are observed. However, the clear lack of effect between the single-task condition and ‘Span-1’ dual-task condition in the first experiment of Doherty and Logie (2016) (Figure 2.2, page 45) would suggest that this is not the case, as would the relatively small drops between the ‘Span -1’ and ‘Span =’ conditions. The relatively small drop in performance between single- and dual-task conditions for both memory and processing in Experiment 1 (Figure 2.4, page 53) suggest a switch of attention in support of above span memory performance rather than an on-going trade-off between the two tasks.

Experiment 2 provides evidence for domain-specific interference as participants’ visual memory span was lower under dual-task conditions. However, the effect of processing load on memory span was still small, with the only statistically significant increase in processing load being between the ‘Span +1’ and ‘Span + 2’ conditions. This suggests that although the initial dual-task cost was larger for visual/spatial dual-tasking (compared to verbal/spatial in Doherty & Logie, 2016, and Experiment 1), the tasks can still operate independently under dual-task conditions. Brown, Forbes, and McConnell (2006) demonstrated that participants may assign names to the stimuli from the visual patterns task, and that ensuring patterns are not easily nameable significantly reduces the measured visual memory span. Our visual patterns were randomly generated trial-to-trial, with no effort to control for the nameability of presented patterns. It is possible that participants were employing some verbal strategy to ‘boost’ single-task visual memory span, and that this
results in artificially high spans that are incompatible with successful dual-task performance. The ‘drop’ between single- and dual-task conditions could therefore be a drop to true visual memory capacity, or a ‘boosted’ visual capacity that can still be supported alongside a concurrent task up until this task becomes too demanding (i.e. in the ‘Span +2’ condition). This default supplementation of memory resources by processing could explain the ‘asymmetry’ between verbal and visual short-term memory reported by Morey, Morey, van der Reijden, and Holweg (2013) (this is discussed in more detail in Chapter 3).

Experiments 1 and 2 provide some preliminary data suggesting that participants’ performance on subtasks can be affected by the load of the concurrent task. Although Doherty and Logie (2016) found no effect of processing load on memory span, a significant effect of memory load on processing accuracy was found. This effect was replicated in Experiment 1, and was found to only occur once memory load was set above participants’ individually measured memory span. However, it is possible that memory performance is already supported by attention in single-task memory span conditions, and that spans measured in this way are artificially high and not conducive to successful dual-tasking.

A possible limitation of our dual-task span procedure is that analysing span does not provide a sensitive enough measure to detect these small drops in performance. A second limitation is that the effect of memory and processing load manipulations were investigated in separate experiments, with any within-experiment analysis of secondary task performance relying on analysis of the final two conditions. These limitations are addressed in Experiments 3-8.
Chapter 3

Dual-Task Visual Memory
3.1 Experiment 3: + Spatial processing

Introduction

Our previous experiments investigated the effects of memory and processing load separately, and within-experiment investigations of contra-task performance were limited to ‘at span’ and ‘above span’ comparisons. Our hypothesis that memory traces can be maintained using phonological and attention-based processes would predict that effects of processing load would be limited to conditions in which the processing task is set ‘above span’: below this level participants’ performance should rely on more automated and/or attention-free rehearsal mechanisms. We discussed one possible limitation being that the span procedure was not sensitive enough to detect the small effects of ‘above span’ processing load on memory accuracy, with weak evidence for this effect being observed in Experiment 1.

Another possible limitation in our first set of experiments was that memory and processing tasks were cross-domain. However, Experiment 2 revealed not only a significant effect of introducing a secondary task on visual memory span, but also a processing load effect when task difficulty was increased beyond participants’ measured capacity. This suggests that cognitive load effects may be more easily observed within-domain due to overlapping representations.

Experiment 3 investigates visual memory and spatial processing dual-tasking, using a titrated-demand procedure similar to that featured in Experiments 1 and 2. The updated procedure allows manipulation of both memory and processing load within participants and within the same experiment, while also increasing the statistical power of analyses by collecting and analysing trial-level data. While Doherty and Logie’s (2016) investigation of dual-task verbal memory span and Experiment 1 both found above-span effects of memory load on processing accuracy, Experiment
2 did not. The updated procedure and the analysis of trial-level data may allow us to detect these effects with a visual patterns task.

The choice of pairing two visual and spatial tasks was motivated by our aim to maximise any trade-off in resources between the two tasks, thereby increasing our chances of detecting different patterns of performance for load increases from ‘below span’ → ‘at span’ → ‘above span’. Although some studies have reported that spatial tasks do not interfere with memory for visual patterns (e.g. Darling et al., 2007; Della Sala et al., 1999), others have shown interference effects between spatial and visual tasks (e.g. Brown & Wesley, 2013). We therefore assume a degree of overlap in visual and spatial representations that, with the separation of visual memory and processing components (Duff & Logie, 1999), should maximise our chances of observing both separation of memory and processing resources for ‘at’ or ‘below span’ conditions, and shared-resource effects when task demands are set ‘above span’.

Our choice of a memory task was also influenced by Brown and Wesley’s (2013) findings regarding participants’ use of multiple coding strategies for visual patterns. Brown and Wesley investigated participants’ strategy use in memory for visual patterns such as those utilised in Experiment 3. Using sets of visual patterns that were either ‘high’ or ‘low’ in their nameability (Brown et al., 2006), Brown and Wesley (2013) compared the effect of AS and ‘executive suppression’ on span. In their first experiment which manipulated interference (2 × 2, AS vs. no AS) and nameability (‘low’ vs. ‘high’), the authors found a small effect of AS, and replicated the nameability effect (Brown et al., 2006), but found no interaction between the two factors. This meant that AS did not remove the nameability benefit as it reduced spans equally in both ‘low’ and ‘high’ nameability conditions. The lack of interaction, and the small effect of AS, is argued as evidence against the sole involvement of the
phonological loop in memory for visual patterns. An analysis of reported strategy use revealed that articulatory suppression reduced reliance on verbal strategies, and marginally reduced the likelihood of combining visual and verbal strategies. Also, those who reported combining both verbal and visual coding strategies outperformed those who relied solely on one strategy or the other, and those who reported only using one strategy demonstrated a greater nameability benefit than those who utilised a dual-coding strategy. These data support Camos et al.’s (2011) finding that participants select rehearsal strategies according to available resources, while suggesting that those who more fully utilise all available strategies display better performance than those who do not.

In a second experiment, Brown and Wesley (2013) assessed the effect of executive suppression on mixed-strategy use. The authors compared participants’ performance on ‘low’ and ‘high’ nameable visual patterns in a control condition (no interference), a spatial interference condition (tapping wooden blocks in a clockwise pattern), and an executive suppression condition (also tapping wooden blocks in a clockwise pattern, but at random intervals). While the TBRS model typically eschews ‘strategy use’ (e.g. use of semantics, mnemonics, etc.) as a mechanism in short-term memory maintenance, the ‘executive loop’ described by Camos and Barrouillet (2014) as being responsible for the refreshing mechanism is said to be available to maintain memory traces so long as it is not occupied with another attention-demanding task. Camos et al. (2011) found that even for a verbal memory task the use of verbal codes can be greatly reduced by both AS but also when use of such codes is not the most efficient method (i.e. for phonologically similar lists). Likewise, when the attention system is occupied with a concurrent task then participants relied on verbal codes and phonological processes (Camos et al., 2009, 2011). Therefore, according to TBRS theory, if differential use of maintenance methods is dependent on the availability of
resources then an executive suppression task should also reduce participants’ ability to utilise mixed-strategies. Indeed, Brown and Wesley (2013) found that (unlike AS) executive suppression in the form of a random tapping task removed the nameability benefit. The authors conclude that while access to the phonological loop does not facilitate the use of verbal codes for visual pattern memory, access to the ‘central executive’ or more generally access to attention is necessary for the nameability benefit.

Our choice to investigate dual-task visual memory performance across different contra-task loads is also influenced by the findings of Morey et al. (2013) regarding the increased vulnerability of visual memory to cross-modal interference compared to verbal memory. Comparing verbal and visual memory performance across a number of experiments, Morey et al. consistently found that memory for visual arrays was more affected by a concurrent verbal memory load than memory for series of letters was affected by concurrent visual memory load. To ensure that the observed asymmetry was due to some innate vulnerability of visual memory, and not due to participants giving greater priority to the verbal memory task, Morey et al. investigated the effect of priority by differentially awarding ‘points’ for performance on one memory task or the other (i.e. 100%/0% weighting for visual/verbal memory tasks respectively, and 70/30, 50/50, 30/70, or 0/100 weightings) based on the procedure of Morey, Cowan, Morey, and Rouder (2011). The authors confirmed that prioritising the visual memory task over the verbal task did not remove the asymmetry in interference effects, but also that the visual memory task demonstrated a more gradated effect of the shift in priority than the verbal task. Verbal memory capacity remained comparable to single-task performance for all priority conditions except for the 0/100:memory/processing condition, and dual-task visual memory load only affected verbal memory capacity in this priority condition.
Morey et al. (2013) concluded that since verbal recoding of their visual arrays was unlikely, and that the asymmetry of visual and verbal memories’ vulnerability to interference remained under instructed priority conditions, that maintenance of visual and verbal material rely on attention processes to different degrees. Maintenance of verbal items is therefore argued to be ‘supported’ by attention, while visual memory is heavily reliant on attention. Morey et al. state that the asymmetry findings are inconsistent with models which assume separate modality-specific stores (namely the MCM), but also models that assume both verbal and visual maintenance rely equally on access to attention, e.g. the ‘early’ TBRS framework (Barrouillet et al., 2004, 2007). Morey et al. (2013) refer to recent developments of the TBRS model (Camos et al., 2009; Barrouillet & Camos, 2010) that argue that there exists a greater number of rehearsal and maintenance procedures for verbal information than for visual representations.

In summary, our choice of memory task for Experiment 3 was motivated by the findings that performance on visual patterns tasks can be ‘boosted’ by verbal strategies and that this benefit is reduced/removed when attention is diverted by a secondary task (Brown et al., 2006; Brown & Wesley, 2013), and that visual memory is reliant on access to attention to a greater degree than verbal memory while also being vulnerable to gradated diversions of attention (Morey et al., 2013). Our choice of processing task is also influenced by the above findings (i.e. that we should expect an effect of diverting attention using any cognitively-demanding dual-task), but also that the evidence for a spatial interference effect on visual memory is mixed (e.g. Darling et al., 2007; Della Sala et al., 1999 vs. Brown & Wesley, 2013). We hypothesise that pairing these two tasks gives us a greater chance of observing the involvement of attention in ‘above span’ visual memory conditions, and also a separation of memory and processing in low demand conditions. Morey et al.’s (2013)
motivation for using a visual-array change-detection task was to reduce the likelihood of the use of verbal codes: we are motivated to use the visual patterns task because we assume that the use of verbal codes involves the same attentional resource required to complete the spatial processing task. We predict that participants will utilise all available resources in the single-task conditions due to the visual rehearsal and maintenance limitations argued by Morey et al. (2013), but particularly when the complexity of the visual patterns exceed their visual memory capacity. Once participants are required to perform visual memory and spatial processing in combination, their ability to support visual memory via other attention/executive processes will be reduced, and so the effect of spatial processing load on memory performance should be more pronounced when tasks are set above participants’ measured span levels.
Method

Participants and Apparatus

Participants were recruited both from the University of Edinburgh Psychology Department’s Participant Pool for first year Psychology students, and through the University of Edinburgh Student and Graduate Employment (SAGE) Career Service. Participants were awarded course credit or paid an honorarium depending on how they were recruited. Twenty-four participants took part in the experiment (8 males and 15 females), with a mean age of 20.8 (range = 18-26).

The experiment was programmed in the E-Prime 2.0 environment. Data were collected using 36cm×27cm displays set at 800×600 pixel resolution and 60Hz refresh rate situated approximately 50cm from participants with a keyboard and computer mouse to record responses.

Procedure

Each participant completed a total of 11 conditions: a single-task visual memory task, a single-task spatial processing task, and nine dual-task conditions. The two single-task conditions always preceded dual-tasking, and were counterbalanced so that half the participants completed the memory task first and half completed the processing task first. The dual-task conditions were counterbalanced in a latin-square design, resulting in nine counterbalanced conditions. The experiment took around 60 minutes to complete.

Single-task visual memory. Single-task visual memory was measured using the same visual pattern task described in Chapter 2 (Experiment 2). Following a 2-5 practice trials, participants’ single-task memory span was recorded as the last level in which they correctly recalled 4/5 grids with 100% accuracy.
3.1. Experiment 3: + Spatial processing

**Single-task spatial processing.** Single-task spatial processing was measured using the task described in Chapter 2. Participants were again given 2-5 practice trials before their span was recorded as the last level at which they achieved 80% accuracy in a block of five trials.

**Dual-task visual memory and spatial processing.** The nine dual-task conditions were combinations of memory and processing loads. Memory and processing loads were titrated according to each individual’s performance in the single-task conditions to give three levels: ‘below span’, ‘at span’, and ‘above span’. Memory load (ML) factors were named ML(-), ML(=), and ML(+), whilst processing load (PL) factors were named PL(-), PL(=), and PL(+). The nine dual-task conditions therefore consisted of every combination of memory and processing load levels (3 × 3). Participants’ accuracy for both memory and processing items was recorded from ten trials carried out in each condition.
3.1. Experiment 3: + Spatial processing

Results

Mean single-task visual memory span was 9.6 black squares ($SD = 1.5$). Mean single-task spatial processing span was 7.6 ($SD = 1.5$).

A note on analyses. Due to the small effect sizes observed in previous experiments, memory and processing data were analysed at trial level via generalised linear mixed effects models (Bolker et al., 2009). Analysing the data set in this way (rather than average performance in blocks and conditions) maximises statistical power (Hoffman & Rovine, 2007; Jaeger, 2008; Dixon, 2008).

Accuracy data were originally recorded as proportion correct, but analysing proportion correct data using conventional methods (e.g. ANOVA) can lead to spurious results largely due to the fact that such analyses do not account for proportion data being bound within the range 0-100 (Dixon, 2008). Type II errors in the detection of interaction effects are a particular problem when using normal models to analyse proportion correct data due to the decreased variance of values close to 0% and 100% accuracy compared to variance at mid-range levels of performance (Jaeger, 2008). Since we are comparing memory and processing between below-span and above-span conditions (where we expect below-span accuracy to be considerably higher than above-span) we must be sure that any detection of effects of contra-task load in the above-span conditions are not due to the aforementioned issues.

One possible solution would be to perform an arcsine transformation on the data, but Dixon (2008) found that while transformations do reduce the possibility of Type II errors for interactions, artefactual evidence may still be found. For this reason Dixon proposed logistic regression as the best alternative to conventional methods. To facilitate such an analysis, our accuracy data were therefore recoded into hits (items in lists recalled correct-in-position, or correct responses to up/down stimuli) and misses, and analysed via logistic regression. Given that we have repeated-
3.1. Experiment 3: + Spatial processing

Figure 3.1: Experiment 3 - Mean memory accuracy across each combination of memory load (ML) and processing load (PL). Data points represent means, while bars represent bootstrapped confidence intervals. Predicted probabilities from Model A (see Table 3.1) are plotted as lines over the mean accuracy data. As such these lines do not perfectly pass through the data means but instead the means predicted by the model. The procedure for generating predicted probabilities is summarised in Appendix B.

Dual-Task Visual Memory

Mean memory accuracies from each memory and processing load manipulation are shown in Figure 3.1. Collapsed across processing load conditions, the unstandardised memory load effect sizes were -1.0% for the ML(-)→ML(=) increase in load, and 2.0% for ML(=)→ML(+) (95% CIs [-2.6%, 0.9%] and [-3.4%, 0.6%] respectively).

Collapsed across memory load conditions, processing load effect sizes were -0.2% for the PL(-) → PL(=) increase, and -0.7% for PL(=) → PL(+) (95% CIs [-2.0%, 1.6%] and [-2.7%, 1.0%]).
### 3.1. Experiment 3: + Spatial processing

Table 3.1: Experiment 3 - Summary of ‘Processing Load’ Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.79 (0.08)***</td>
<td>1.92 (0.08)***</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>−0.01 (0.05)</td>
<td>−0.01 (0.05)</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>−0.14 (0.04)**</td>
<td>−0.13 (0.04)**</td>
</tr>
<tr>
<td>[3] PL (-) to (=)</td>
<td>0.04 (0.05)</td>
<td>0.09 (0.05)</td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>−0.07 (0.05)</td>
<td>−0.03 (0.05)</td>
</tr>
<tr>
<td>1:3</td>
<td>0.02 (0.12)</td>
<td>0.00 (0.12)</td>
</tr>
<tr>
<td>1:4</td>
<td>0.08 (0.11)</td>
<td>0.08 (0.11)</td>
</tr>
<tr>
<td>2:3</td>
<td>0.10 (0.12)</td>
<td>0.11 (0.12)</td>
</tr>
<tr>
<td>2:4</td>
<td>−0.24 (0.11)*</td>
<td>−0.22 (0.11)*</td>
</tr>
<tr>
<td>ProcErrors</td>
<td>−0.24 (0.11)*</td>
<td>−0.08 (0.01)***</td>
</tr>
<tr>
<td>AIC</td>
<td>8583.85</td>
<td>8545.46</td>
</tr>
<tr>
<td>BIC</td>
<td>8641.81</td>
<td>8609.21</td>
</tr>
<tr>
<td>Log Likelihood</td>
<td>−4281.93</td>
<td>−4261.73</td>
</tr>
<tr>
<td>Num. obs.</td>
<td>2430</td>
<td>2430</td>
</tr>
<tr>
<td>Num. groups: Participant</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>

* ***p < 0.001, **p < 0.01, *p < 0.05

**Processing Load.** Predictors included memory load and processing load (each with three levels: [], [=], and [+]), and memory load:processing load interactions. Memory and processing load factor levels were compared via backward difference coding: memory performance at each factor level was compared with the preceding condition (X. Chen, Ender, Mitchell, & Wells, 2003). In order to account for the effect of concurrent processing task accuracy as reported by Lewandowsky et al. (2009), we also ran a second model (Model B) which included the number of errors for each trial as an additional variable for processing errors (‘ProcErrors’). If post-error processing captures attention then memory accuracy may be affected in trials with more processing task errors than in trials with fewer errors. Any effect of the number of processing task errors is therefore of interest, and should also be controlled for when testing for an effect of ‘cognitive load’: Lewandowsky and Oberauer’s reanalysis of Portrat et al.’s (2008) data found that when post-error processing was accounted
for the effect of cognitive load disappeared.

Table 3.1 displays coefficient estimates and associated standard errors from Models A and B. Both models contain a statistically significant memory load effect, but only for the ML(→)→ML(+) increase. The coefficients for each increase in processing load were not statistically significant, although a significant memory load:processing load interaction was found in both models (labelled ‘2:4’ in Table 3.1). This interaction is easy to interpret alongside the summarised data shown in Figure 3.1, as memory accuracy is poorer when both tasks were set above participants’ spans (ML[+] and PL[+] data point). Model B also contains a statistically significant effect of processing errors on memory accuracy.

Interpreting the statistically significant coefficients in Model B in Table 3.1 in terms of the likelihood of giving a correct or incorrect response, participants were $e^{-0.13} = 0.88$ times as accurate in the ML(+) condition compared to in the ML(=) condition (i.e. $e^{-0.13} = 1.14$ times more likely to produce an incorrect response). For the ML(+) and PL(+) combination of loads, participants were $e^{-0.22} = 1.25$ times more likely to make an error compared to the ML(=) and PL(=) load combination. For every error made in the processing task, participants were $e^{-0.08} = 1.08$ times more likely to produce an error in the memory task.

**Retrievals-per-second (RPS)** By virtue of the titrated-load procedure participants were only exposed to small changes in ‘cognitive load’ as defined by the TBRS model in order to avoid requiring participants to attempt tasks set at levels well beyond their abilities. Studies which report an effect of cognitive load (measured in retrievals-per-second) often test a wider range of values than our participants were exposed to (e.g. Barrouillet et al., 2004, 2007). Fortunately, it is possible to analyse the general effect of cognitive load across all tested values by analysing the effect of increasing retrievals-per-second (RPS) across all participants using multilevel re-
Table 3.2: Experiment 3 - Summary of RPS Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.79 (0.08)**</td>
<td>1.92 (0.08)**</td>
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<td>-0.01 (0.05)</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>-0.14 (0.04)**</td>
<td>-0.13 (0.05)**</td>
</tr>
<tr>
<td>RPS</td>
<td>-0.03 (0.11)</td>
<td>0.17 (0.11)</td>
</tr>
<tr>
<td>1:RPS</td>
<td>0.30 (0.14)*</td>
<td>0.29 (0.14)*</td>
</tr>
<tr>
<td>2:RPS</td>
<td>-0.39 (0.13)**</td>
<td>-0.35 (0.13)**</td>
</tr>
<tr>
<td>ProcErrors</td>
<td></td>
<td>-0.08 (0.01)**</td>
</tr>
</tbody>
</table>

| AIC                     | 8576.50       | 8537.94       |
| BIC                     | 8617.07       | 8584.30       |
| Log Likelihood          | -4281.25      | -4260.97      |
| Num. obs.               | 2430          | 2430          |
| Num. groups: Participant| 26            | 26            |

***p < 0.001, **p < 0.01, *p < 0.05

In our experiment RPS referred to the number of lexical decisions:time ratio of the retention interval: e.g. 5 lexical decisions/5000ms would give an RPS value of ‘1’.

As before, two logistic regression models were fitted to the data: Model A contained the predictors ‘memory load’ (treated as a factor) and RPS (treated as a continuous variable, with tested values 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8)\(^1\) and the memory load:RPS interaction, with Model B including the processing errors variable.

The results of these analyses are shown in Table 3.2. Both models contain statistically significant ML(=)→ML(+) memory load effects. As with the analysis of processing load, the overall effect of RPS is not statistically significant. However both memory load:RPS interactions were statistically significant: a positive effect of RPS for the ML(-)→ML(=) increase and a negative effect for the ML(=)→ML(+) increase. As before, Model B also contains a statistically significant effect of processing errors.

\(^1\)These values were centred for the analyses summarised in Table 4.2, and in all future RPS analyses reported in this thesis.
In terms of the likelihood of providing a correct or incorrect response, the coefficient for the ML(=)→ML(+) means that participants were $\frac{1}{e^{-0.13}} = 1.13$ times more likely to produce an error in the latter condition. For the ML(-)→ML(=) increase in memory load, participants were $e^{0.29} = 1.34$ times more likely to produce a correct response with each increase in RPS, compared to the non significant main effect of RPS. For the ML(=)→ML(+) increase, participants were $\frac{1}{e^{-0.35}} = 1.42$ times more likely to make an error. As with the analysis of processing load, participants were $\frac{1}{e^{-0.08}} = 1.08$ times were more likely to produce an error in the memory task for every error made in the processing task.

**Dual-Task Spatial Processing**

Figure 3.2 displays mean processing accuracy across all conditions. Collapsed across memory load conditions, the unstandardised processing load effect sizes were -5.9% for the PL(-) → PL(=) increase in processing load, and -2.9% for the PL(=) → PL(+) increase (95% CIs[-7.7%, -4.0%] and [-5.2%, -0.6%] respectively).

Collapsed across processing load conditions, memory load effect sizes were -0.8% for the ML(-)→ML(=) increase, and -0.9% for the ML(=) → ML(+) increase (95% CIs[-2.7%, 1.2%] and [-3.1%, 1.3%]).

**Memory Load.** Dual-task spatial processing accuracy was analysed using the same procedure as Model A in the analysis of memory accuracy. The results of this analysis show no effect of memory load on processing accuracy, and no significant interactions. Participants were $\frac{1}{e^{-0.35}} = 1.42$ times more likely to make a processing task error in the PL(=) condition compared to the PL(-) condition, and $\frac{1}{e^{-0.14}} = 1.15$ times more likely to produce an error in the PL(+) condition compared to the PL(=) condition.
3.1. Experiment 3: + Spatial processing

Figure 3.2: Experiment 3 - Mean processing accuracy (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities from the model (see Table 3.3) are plotted over mean accuracy data.

Table 3.3: Experiment 3 - Summary of Logistic Regression on Processing Accuracy

| Model 1 | (Intercept) 1.38 (0.10)**  
[1] PL (−) to (=) −0.35 (0.05)***  
[2] PL (=) to (+) −0.14 (0.04)***  
[3] ML (−) to (=) −0.02 (0.05)  
[4] ML (=) to (+) −0.05 (0.05)  
1:3 0.18 (0.12)  
1:4 −0.10 (0.10)  
2:3 −0.05 (0.12)  
2:4 −0.17 (0.10)  
| Num. obs. 2430  
| Num. groups: Participant 26  

***p < 0.001, **p < 0.01, *p < 0.05
Discussion

The results from Experiment 3 revealed a significant effect of spatial processing load on memory accuracy only when both tasks were set above participants’ individually measured span. The retrievals-per-second (RPS) analysis contained a similar interaction, with a larger RPS effect between the ML(=)→ML(+) memory loads. For each analysis of memory accuracy a significant main effect of processing load and RPS was not found. Also, for both analyses, the increase in memory load between the ML(-)→ML(=) conditions was not statistically significant. The data summarised in Figure 3.1 reveals that the significant memory load:processing load interaction (and likely the [2]:RPS interaction summarised in Table 3.2) are driven by the fact that an effect of memory load is only for the combination of ML(+) & PL(+).

In the analysis of processing accuracy, no effect of memory load was found for either the ML(-)→ML(=) or ML(=)→ML(+) increases in load. Unlike the analysis of memory accuracy, the effect of processing load on processing accuracy was present for both increases in load.

The results from Experiment 3 support our hypothesis that memory performance would be affected when both tasks were set above participants’ spans. However the fact that the memory load manipulation (one extra black square to remember in the visual pattern matrix) did not elicit an effect on memory accuracy except when both tasks were set above span makes it difficult to interpret the effect of processing load on visual memory maintenance.

Our motivation for pairing a visual patterns task with a spatial processing task was to maximise any trade-off between the two tasks. However, as discussed in the introduction to this chapter, visual short-term memory has been argued to be particularly vulnerable to interference both across- (Morey et al., 2013) and within domains (Brown & Wesley, 2013). In the discussion of Experiments 1 and 2 we
hypothesised that single-task span may already rely on additional resources, and so may be an artificially high estimation of participants’ domain-specific capacity. Considering that visual memory capacity may be considerably lower than verbal memory due to there being fewer specialised rehearsal/maintenance mechanisms available for the former compared to the latter, the additional difficulty of co-ordinating a visual memory and spatial processing task may ‘wash out’ the memory load effect in dual-task conditions. This is supported by the lack of effect of memory load on processing accuracy in both this experiment and in Experiment 2 (see Figure 2.7, page 64). Our interpretation was that the lack of memory load effect in Experiment 2 was due to all available resources being utilised simply to co-ordinate tasks with similar stimuli, and so any additional ‘switch’ of attention could not be observed when memory capacity was exceeded. Also, no effect of processing load on visual memory accuracy was observed between the ‘at span’ and ‘above span’ conditions in Experiment 2 (see Figure 2.6, page 63). We analysed trial-level data in Experiment 3 in an effort to detect smaller changes in accuracy than analysis of means permitted, but the data summarised in Figure 3.1 (page 80) suggest that our failure to detect an effect of memory load is not an issue of statistical power.

We reason that the potential overlap in representations between the visual memory task and spatial processing task, coupled with the findings discussed previously regarding visual memory’s greater reliance on attention compared to verbal memory, both contribute to a pattern of interference that makes separating an effect of processing load on memory accuracy from an effect of memory load based on an artificially high single-task memory span difficult. Experiment 4 aimed to simplify the interaction between memory and processing tasks by substituting a verbal processing task in place of the spatial processing task utilised in previous experiments. Contrary to our initial predictions, we expect that using a processing task with less overlap
in representation will allow us to detect both an effect of a diversion of attention from maintenance of demanding memory loads resulting in lower memory accuracy, as well as a lack of effect of processing load on memory accuracy at low memory loads, whilst additionally preserving the effect of the ML(-)→ML(=)→ML(+ ) load manipulations.
3.2 Experiment 4: + Verbal processing

Introduction

Experiment 4 aims to replicate the ‘above span’ memory load:processing load interaction effect observed in Experiment 3, whilst maintaining the distinction between each memory load condition. Experiment 2 revealed a significant effect of spatial processing load on visual memory span at the ‘Span +2’ level, but Figure 2.6 (page 63) suggests that a small effect may be present between the ‘at span’ and ‘above span’ conditions.

The analysis of processing performance in Experiment 3 revealed no significant effects of memory load on spatial processing accuracy (although, unlike in the analysis of memory performance, the processing load manipulation affected processing accuracy). This same pattern was observed in Experiment 2, which we interpreted as being due to an inherent difficulty of co-ordinating dual-tasks with overlapping representations. The substitution of a verbal processing task in Experiment 4, in place of the spatial task used in previous experiments, should help differentiate between interference between the representations of both tasks and interference due to a shared reliance on an attention-based resource for high load memory and processing conditions.

As discussed in the report of Experiment 3, we predicted that the collection and analysis of trial-level data will allow us to detect subtle changes in memory and processing performance in Experiment 4.
Method

Participants and Apparatus

Twenty-four participants were recruited to take part in the experiment, but one participant’s data were excluded from the analyses due to a technical fault with the experimental software. The resulting sample consisted of 9 males and 14 females, with a mean age of 21.7 (range = 18-24). The experiment was conducted using the same equipment as Experiment 3.

Procedure

The experiment followed the same procedure as Experiment 3, except for the substitution of a speeded lexical decision task in place of the spatial processing task used in previous experiments.

Single-task verbal processing. Single-task verbal processing was measured via a speeded lexical decision task. Participants were presented a number of letter strings located in the centre area of the screen over the course of 5000ms. Each letter string was either an English word or a nonword. The procedure for generating words and nonwords is detailed in Appendix C.

Each word/nonword appeared for 5000ms/p, where p = total number of items to be processed. Participants were instructed to respond to real words by pressing a key marked with a ‘tick’, and nonwords by pressing a key marked with a ‘cross’. Participants were again given 2-5 practice trials. Following these practice trials participants started with a block of five trials with a presentation rate of five letter strings over 5000ms, with each successive block increasing the number of words/nonwords which appeared in the 5000ms interval. Participants continued in this fashion until they failed to answer at least 80% of items correctly at a level, and their span was recorded as the previous level.
3.2. Experiment 4: + Verbal processing

Results

Mean single-task visual memory span was 9.3 ($SD = 2.1$), and mean single-task spatial processing span was 7.2 ($SD = 1.1$).

Dual-Task Visual Memory

Figure 3.3 displays mean memory accuracies for each combination of memory and processing load. Collapsed across processing load conditions, the unstandardised effect sizes for each increase in memory load were -2.2% and -1.3% (95% CIs[-3.5%, -0.7%] and [-2.9%, 0.4%]).

Collapsed across memory load conditions processing load effect sizes for each increase in load were -0.9% and -0.6% (95% CIs[-2.6%, 0.6%] and [-2.6%, 1.4%] respectively).

Processing Load. Memory accuracy was analysed using the same methods as described in Experiment 3. The results of the analyses (summarised in Table 3.4) reveal significant main effects of memory load, but no effects of processing load and no interactions.

Interpreting the statistically significant coefficients in Table 3.4 in terms of the likelihood of giving a correct or incorrect response, participants were $\frac{1}{e^{-0.29}} = 1.22$ times more likely to produce an error in the memory task in the ML(=) condition compared to the ML(-) condition. Participants were $\frac{1}{e^{-0.11}} = 1.12$ times more likely to produce an error in the ML(+) condition compared to the ML(=) condition.

Retrievals-per-second (RPS) The effect of RPS was analysed in the same way as in Experiment 3. The results are summarised in Table 3.5. Memory load coefficients were the same as observed in the analysis of processing load. RPS was statistically significant in Model A (participants were $\frac{1}{e^{-0.34}} = 1.34$ times more likely
Table 3.4: Experiment 4 - Summary of ‘Processing Load’ Logistic Regression Models

<table>
<thead>
<tr>
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<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.98 (0.12)**</td>
<td>2.03 (0.12)**</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>−0.20 (0.05)**</td>
<td>−0.20 (0.05)**</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>−0.11 (0.05)*</td>
<td>−0.11 (0.05)*</td>
</tr>
<tr>
<td>[3] PL (-) to (=)</td>
<td>−0.05 (0.05)</td>
<td>−0.04 (0.05)</td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>−0.04 (0.05)</td>
<td>−0.01 (0.05)</td>
</tr>
<tr>
<td>1:3</td>
<td>0.00 (0.13)</td>
<td>0.01 (0.13)</td>
</tr>
<tr>
<td>1:4</td>
<td>−0.18 (0.12)</td>
<td>−0.18 (0.12)</td>
</tr>
<tr>
<td>2:3</td>
<td>−0.07 (0.13)</td>
<td>−0.07 (0.13)</td>
</tr>
<tr>
<td>2:4</td>
<td>−0.06 (0.12)</td>
<td>−0.06 (0.12)</td>
</tr>
<tr>
<td>ProcErrors</td>
<td></td>
<td>−0.03 (0.02)</td>
</tr>
</tbody>
</table>

AIC: 7265.52 7263.99  
BIC: 7323.10 7327.33  
Log Likelihood: −3622.76 −3621.00  
Num. obs.: 2340 2340  
Num. groups: Participant: 26 26

***p < 0.001, **p < 0.01, *p < 0.05

Figure 3.3: Experiment 4 - Mean memory accuracy (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities from the model (see Table 3.4) are plotted over mean accuracy data.
### 3.2. Experiment 4: + Verbal processing

Table 3.5: Experiment 4 - Summary of RPS Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.98 (0.12)***</td>
<td>2.02 (0.12)***</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>-0.20 (0.05)***</td>
<td>-0.20 (0.05)***</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>-0.11 (0.05)*</td>
<td>-0.11 (0.05)*</td>
</tr>
<tr>
<td>RPS</td>
<td>-0.29 (0.13)*</td>
<td>-0.18 (0.14)</td>
</tr>
<tr>
<td>1:RPS</td>
<td>0.11 (0.21)</td>
<td>0.12 (0.21)</td>
</tr>
<tr>
<td>2:RPS</td>
<td>-0.30 (0.19)</td>
<td>-0.31 (0.19)</td>
</tr>
<tr>
<td>ProcErrors</td>
<td></td>
<td>-0.03 (0.02)</td>
</tr>
</tbody>
</table>

AIC 7263.67         BIC 7262.43
Log Likelihood      -3624.84         -3623.22
Num. obs.           2340            2340
Num. groups: Participant 26       26

***p < 0.001, **p < 0.01, *p < 0.05

To produce an error with each increase in RPS. Controlling for the number of errors in Model B reduces the coefficient to a non-significant value.

**Dual-Task Spatial Processing**

Mean spatial processing accuracies are shown in Figure 3.4. Effect sizes for each increase in processing load were -4.5% and -10.0% (95% CIs[-5.6%, -3.3%] and [-12.4%, -7.9%] respectively). The coefficient estimates from Table 3.6 reveal that participants were $\frac{1}{e^{-0.38}} = 1.46$ times more likely to produce an error in the PL(=) condition compared to the PL(-) condition, and $\frac{1}{e^{-0.65}} = 1.92$ times more likely to produce an error in the PL(+) condition than in the PL(=) condition.

Memory load effect sizes were -0.3% for the ML(-) → ML(=) increase, and -0.3% for the ML(=) → ML(+) increase (95% CIs[-2.2%, 1.5%] and [-1.8%, 1.2%]). The results of the regression analysis of processing accuracy revealed that these effects were non-significant.
3.2. Experiment 4: + Verbal processing

Figure 3.4: Experiment 4 - Mean processing accuracy (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities from the model (see Table 3.4) are plotted over mean accuracy data.

Table 3.6: Experiment 4: Summary of Logistic Regressions on Processing Accuracy

| Model 1 |  
|---------|---------|  
| (Intercept) | 1.62 (0.07)***  
| [1] PL (-) to (=) | 0.38 (0.06)***  
| [2] PL (=) to (+) | 0.65 (0.05)***  
| [3] ML (-) to (=) | 0.03 (0.05)  
| [4] ML (=) to (+) | 0.04 (0.05)  
| 1:3 | 0.16 (0.15)  
| 1:4 | 0.08 (0.12)  
| 2:3 | 0.07 (0.14)  
| 2:4 | 0.10 (0.11)  

Num. obs. | 2340  
Num. groups: Participant | 26  

***p < 0.001, **p < 0.01, *p < 0.05
3.2. Experiment 4: + Verbal processing

Discussion

The results from Experiment 4 revealed a significant effects of memory load on visual memory accuracy for both the ML(-)→ML(=) and ML(=)→ML(+) increases in load (effects that were absent in Experiment 3). No effects of processing load on memory accuracy were detected, and (unlike in Experiment 3) a memory load:processing load interaction was not detected when both tasks were set above span. By analysing the effect of processing load across all possible values in the analysis of RPS, an overall effect of verbal processing load was detected (see Table 3.5, page 93). However, when the number of processing errors were accounted for this effect was no longer present, suggesting that (as previously demonstrated by Lewandowsky & Oberauer, 2009) the root cause of any disruptive effect of concurrent processing on memory maintenance is possibly due to error processing disrupting dual-tasking ability.²

The plotted model predictions in Figure 3.3 (page 92) suggests a pattern of data fitting with our hypothesis, but the visual memory accuracy data are simply too variable to reliably predict these effects.

For the verbal processing task, an effect of processing load on accuracy was found but no effects of memory load and no interactions were detected.

In summary, the substitution of a verbal memory task in place of the spatial task used in Experiment 3 allowed detection of an overall memory load effect on memory accuracy, but data appear too variable to reliably detect any effects of processing load. The analysis of processing accuracy data, and the summarised data in Figure 3.4 (page 94) would suggest that any resources involved in the lexical decision task are not diverted to support visual memory performance.

²Experiment 9 in Chapter 6 (page 167) investigated the effect of instructed task priority on memory and processing performance, and found that participants’ performance on the memory task was affected by asking participants to shift their attention to the processing task. An alternative explanation of the effect of processing errors on memory accuracy could therefore be that error rates shift participants’ priorities to the processing task, and performance on the memory task is sacrificed in an attempt to reduce errors on the choice-RT task.
3.3 General Discussion of Experiments 3 & 4.

Experiments 3 and 4 were designed to develop the procedure used in Doherty and Logie (2016) and Experiments 1 and 2 to allow an investigation of the effects of memory and processing load on performance on each task.

As discussed, our motivation for using a visual memory task was founded on previous research demonstrating a tendency for participants to give visual patterns verbal labels (Brown et al., 2006; Brown & Wesley, 2013), and that visual memory appears more reliant on switches of attention compared to verbal memory (Morey et al., 2013).

In practice, however, the visual patterns task did not facilitate the detection of clear resource-independent and resource-sharing effects. In Experiment 3 the effect of memory load on memory accuracy was not present, and no effect of memory load on processing accuracy was observed. Switching to a verbal processing task in Experiment 4, the effect of memory load was retained in the dual-task conditions. As with Experiment 3, no effect of memory load on processing accuracy was observed.

It therefore appears that the fact that the visual patterns task can be approached in a number of ways makes it difficult to measure a consistent pattern of behaviour. Indeed, Brown and Wesley (2013) noted that only some participants reported using both verbal and visual encoding strategies, and that these participants demonstrated different patterns of performance from those who reported using a single encoding strategy. In a study of the generalisability of the phonological similarity and word length effects in verbal memory span, Logie et al. (1996) found that almost half of participants failed to demonstrate one or more of these highly replicated affects. Importantly, Logie et al. (1996) also found that a participant demonstrating or failing to demonstrate one or both of the verbal memory effects did not predict whether the same participant would demonstrate the effect in a follow-up session. It is therefore
possible that participants vary not only on how they approach the visual patterns task, but also on how they approach the task in subsequent dual-task conditions following the single-task memory span measure.

The clearest cross-task effect observed in these two experiments is the above-span effect shown in Figure 3.1 (page 80). Assuming that the lack of memory load effect on memory performance was due to the inherent difficulty of co-ordinating the visual and spatial tasks, the fact that performance drops considerably when task demands exceed measured single-task ability supports the hypothesis that above-span performance can result in a large cost to performance compared to when task demands are set within participants’ abilities. However, as discussed it appears that the disruption to memory performance was due to an increased error rate in the high processing load condition since the analysis of retrievals-per-second (RPS) removed any effect of processing task demand.

One possible solution would be to use a change-detection task that permits estimation of participants’ visual memory capacity (e.g. Cowan, 2001). Bengson and Luck (2016) demonstrated that instructing participants to use different strategies results in different estimates of capacity. The authors investigated whether instructing participants to attempt to remember a subset of presented items, or to try and memorise the whole array, resulted in different capacity estimates compared to a control condition in which the instruction to participants was simply to “do your best”. Contrary to the predictions based on the literature that low capacity estimates may be obtained when participants are given high set sizes as they try to encode the entire array, Bengson and Luck found that instructing participants to attempt to encode the entire visual array resulted in higher capacity estimates than control conditions.

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3A cursory comparison of the standard deviations of visual memory spans from Experiments 3 & 4 to the verbal memory spans measured in Experiments 5-9 supports this notion.
3.3. General Discussion of Experiments 3 & 4.

These findings suggest that a change-detection task may allow investigation of differential encoding strategies for high and low concurrent processing loads, but a number of caveats exist that preclude the use of change detection tasks to investigate our hypotheses. Although Bengson and Luck (2016) found that different strategies can produce different capacity estimates, without specifically instructing participants to utilise one strategy we would not know how participants were approaching the task. While this is true for most tasks, the fact that such approaches can cause large changes in capacity estimates using the same set sizes would make it difficult to tease apart changes in the measure of overall memory capacity \((k, \text{ Cowan, 2001})\) due to the effects described by Bengson and Luck (2016) or from shifts of attention such as those described by Morey et al. (2013). Finally, since our manipulation of memory load is based on increasing the number of items to be remembered, the change-detection method of calculating capacity cannot easily be adapted due to the assumption that a participants have a ‘true’ capacity and that estimates from different list lengths should therefore converge on similar values.

Therefore, based on the difficulty in interpreting the memory data provided by the visual patterns task, and the unsuitability of change-detection and capacity measures for adaption to our titrated demand procedure, we decided to return to a verbal memory task for Experiments 5-9.
Chapter 4

Experiment 5: Dual-Task Verbal Memory & Spatial Processing
4.1 Introduction

Our initial investigations of titrated demand using verbal memory (Doherty & Logie, 2016 and Experiment 1) revealed an above-span effect of processing load on memory performance (Figures 2.3 & 2.4, pages 46 & 53). The manipulation of verbal memory load in Experiment 1 resulted in clear effects on memory accuracy (Figure 2.5, page 54). However, Experiment 2 (page 59) only remeasured visual memory span under different processing loads, and did not compare memory performance between different visual pattern task ‘levels’. We assumed that the changes in visual pattern complexity with each increase in memory load would result in comparable drops in memory accuracy to those observed in Experiment 1, but this was not the case. Alternative visual memory tasks were considered (as discussed in the previous section), but a suitable candidate was not identified. Considering that research in to the TBRS model (and indeed working memory research in general) has focussed on memory for verbal items, and that the TBRS model does not include a specialised visual memory store or mechanisms for visual memory rehearsal (see Barrouillet & Camos, 2014), we decided to switch back to verbal memory tasks for future experiments.

Based on the previously discussed findings of Camos et al. (2009, 2011), and of Vergauwe et al. (2014), we predicted that the experimental procedure described in Chapter 3 would allow detection of small changes in verbal memory performance caused by increased reliance on attention resources in high load conditions. The large memory load effects observed in Experiment 1 also mean that these additional effects of processing load on the participants’ ability to recruit these additional resources should be detectable and separable from simple dual-task costs and costs relating to error processing.

Experiment 5 therefore follows the same procedure as Experiment 3, except
for the substitution of a verbal memory task (letter span) for the visual patterns task. In line with our overarching hypothesis, we predict that participants’ memory performance will only be affected by the concurrent processing task once its demand exceeds participants’ single-task processing span. Although the representation of verbal and spatial material should not overlap to a great degree, it has been shown that visually presented verbal items can be coded visually (Logie et al., 2000; Saito et al., 2008; Logie, Saito, et al., 2016). We therefore also predict a cost to processing performance once dual-task memory load is set above participants’ span.
4.2 Method

Participants, Materials, & Procedure

Participants were recruited in the same way as in the experiments reported in Chapter 3. One participant was omitted from the analyses due to data corruption. This resulted in the following sample: \( n = 26 \), (9 males, 17 females), mean age = 21.7, range = 18-25.

The experiment was programmed in the E-Prime 2.0® environment and conducted using a 15-inch LCD monitor set at a 1280×1024 pixel resolution and 60Hz refresh rate. Responses were collected via the keyboard.

Experiment 5 featured a letter span task instead of the digit span task described in Chapter 2. The stimuli included all letters except vowels, and the letter ‘w’. Whereas the digit span stimuli were presented one-by-one in the centre of the screen, the letter span stimuli were presented as a complete list. The presentation time of memory stimuli remained the same as in previous experiments, set at 1000ms/item.

The spatial processing task proceeded the same as described in previous chapters.
4.3 Results

Mean single-task verbal memory span was 6.19 ($SD = 1.14$), and mean single-task spatial processing span was 8.12 ($SD = 1.91$).

**Dual-Task Verbal Memory.**

Figure 4.1 displays mean memory accuracy from each memory and processing load condition. Collapsed across processing load conditions, unstandardised memory load effect sizes were -8.2% for ML(-)$\rightarrow$ML(=) and -9.8% for ML(=)$\rightarrow$ML(+) (95% CIs [-11.6%, -5.7%] and [-12.4%, -9.8%] respectively). Collapsed across memory load conditions the effect size between PL(-)$\rightarrow$PL(=) was near-zero (0.01%, 95% CI[-2.6%, 2.4%]), while the effect size between PL(=)$\rightarrow$PL(+) was -3.6% (95% CI[-6.1%, 1.2%]).

**Processing Load.** Table 4.1 displays coefficient estimates from Models A and B alongside standard errors. The effect of increasing memory load is clear in both models (see Figure 4.1). However, accuracy is only affected by processing load when the spatial processing task is set above participants’ individual spans. The significant interaction (labelled ‘2:3’ in Table 4.1) refers to the small increase in accuracy between PL(-) and PL(=) loads in the ‘at span’ (ML[=]) condition. Model B also contains a statistically significant effect of processing errors (labelled ‘ProcErrors’ in Table 4.1).

Interpreting the statistically significant coefficients in Model B in Table 5.1 in terms of the likelihood of giving a correct or incorrect response, participants were $\frac{1}{e^{-0.43}} = 1.54$ times more likely to produce an error in the ML(=) condition than in the ML(-) condition. Memory task errors were $\frac{1}{e^{-0.44}} = 1.55$ times more likely in the ML(+) condition compared to the ML(=) condition. Participants were $\frac{1}{e^{-0.16}} =$
Table 4.1: Experiment 5 - Summary of ‘Processing Load’ Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.37 (0.10)***</td>
<td>1.64 (0.10)***</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>-0.44 (0.06)***</td>
<td>-0.43 (0.06)***</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>-0.46 (0.05)***</td>
<td>-0.44 (0.05)***</td>
</tr>
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<td>[3] PL (-) to (=)</td>
<td>0.01 (0.05)</td>
<td>0.08 (0.05)</td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>-0.26 (0.05)***</td>
<td>-0.16 (0.05)**</td>
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<td>-0.09 (0.12)</td>
</tr>
<tr>
<td>2:3</td>
<td>0.27 (0.14)*</td>
<td>0.28 (0.14)*</td>
</tr>
<tr>
<td>2:4</td>
<td>-0.05 (0.11)</td>
<td>-0.04 (0.11)</td>
</tr>
<tr>
<td>ProcErrors</td>
<td></td>
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<tr>
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<tr>
<td>BIC</td>
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<td>8095.14</td>
</tr>
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<td>Log Likelihood</td>
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<td>-4004.90</td>
</tr>
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<td>Num. obs.</td>
<td>2340</td>
<td>2340</td>
</tr>
<tr>
<td>Num. groups: Participant</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>

***p < 0.001, **p < 0.01, *p < 0.05

1.17 times more likely to produce an error in the PL(+) condition compared to the PL(=) condition. Regarding the interaction effect, participants were \(e^{0.28} = 1.32\) times more accurate in the ML(=) condition when processing load was set at span (‘=’) compared to when it was set below span (‘-’), after the effects of memory load on accuracy are accounted for. Participants were \(\frac{1}{e^{0.15}} = 1.16\) times more likely to produce an error in the memory task for each error made in the processing task.

**Retrievals-per-second (RPS).** The results of these analyses are shown in Table 4.2. Both models contain statistically significant effects of memory load similar to those observed in the processing load analysis. Model A also contains a significant RPS effect, as participants were \(\frac{1}{e^{0.49}} = 1.63\) times more likely to produce an error in the memory task for each increase in RPS.

Model A also contains a memory load:RPS interaction between ML(=) and ML(+) conditions, suggesting that RPS only has a negative effect on memory accu-
4.3. Results

Figure 4.1: Experiment 5 - Mean memory accuracy (with bootstrapped confidence intervals) across each combination of memory load and processing load (PL). Predicted probabilities from Model B (see Table 4.1) are plotted over mean accuracy data.

racy when memory load is set above participants’ span. Interpreting the interaction coefficient in terms of the likelihood of providing a correct or incorrect memory task response, participants were unaffected by for the ML(−)→ML(=) increase in memory load but were \[ \frac{1}{e^{-0.23}} = 1.26 \] times more likely to produce an error for the ML(=)→ML(+) increase for each increase in RPS.

Model B reveals a statistically significant effect of processing errors on memory accuracy, with participants being \[ \frac{1}{e^{-0.16}} = 1.16 \] times more likely to produce an error in the memory task for each error made in the processing task. The overall effect of RPS and the interaction are non-significant when processing errors are controlled for in this way.
### Table 4.2: Experiment 5 - Summary of RPS Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.37 (0.10)***</td>
<td>1.64 (0.10)***</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>−0.43 (0.06)***</td>
<td>−0.42 (0.06)***</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>−0.45 (0.05)***</td>
<td>−0.43 (0.05)***</td>
</tr>
<tr>
<td>RPS</td>
<td>−0.49 (0.12)***</td>
<td>0.09 (0.12)</td>
</tr>
<tr>
<td>1:RPS</td>
<td>0.24 (0.14)</td>
<td>0.26 (0.14)</td>
</tr>
<tr>
<td>2:RPS</td>
<td>−0.23 (0.11)*</td>
<td>−0.22 (0.11)</td>
</tr>
<tr>
<td>ProcErrors</td>
<td>−0.15 (0.01)***</td>
<td></td>
</tr>
<tr>
<td>AIC</td>
<td>8152.76</td>
<td>8034.85</td>
</tr>
<tr>
<td>BIC</td>
<td>8193.07</td>
<td>8080.91</td>
</tr>
<tr>
<td>Log Likelihood</td>
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<td>−4009.42</td>
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<tr>
<td>Num. obs.</td>
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<td>2340</td>
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<td>Num. groups: Participant</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>

***p < 0.001, **p < 0.01, *p < 0.05
Dual-Task Spatial Processing.

Mean processing accuracy across all conditions is shown in Figure 4.2. Collapsed across memory load conditions, the unstandardised processing load effects were $-3.3\%$ and $-5.5\%$ (95% CIs$[-5.1\%, -1.5\%]$ and $[-7.6\%, -3.6\%]$ respectively). Memory load effect sizes were $-1.2\%$ (95% CI$[-2.9\%, 0.4\%]$) for the ML($-$)$\rightarrow$ML($=$) increase, and $-2.3\%$ (95% CI$[-3.7\%, -0.9\%]$) for the ML($=$)$\rightarrow$ML($+$) increase in memory load.

Table 4.3 summarises the regression analysis, and reveals statistically significant effects of both processing and memory load on spatial processing accuracy. However, the effect of memory load is only statistically significant between the ML($=$) $\rightarrow$ ML($+$) conditions.

Interpreting the statistically significant coefficients, participants were $\frac{1}{e^{-0.23}} = 1.26$ more likely to produce an error in the PL($=$) condition compared to the PL($-$) condition, and $\frac{1}{e^{-0.3}} = 1.35$ times more likely in the PL($+$) condition compared to the PL($=$) condition. Participants were $\frac{1}{e^{-0.11}} = 1.12$ times more likely to produce an error in the ML($+$) memory load condition than in the ML($=$) condition.
Table 4.3: Experiment 5 - Summary of Logistic Regressions on Processing Accuracy

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficient (SE)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.34 (0.06)***</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>[1] PL (-) to (=)</td>
<td>-0.23 (0.05)***</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>[2] PL (=) to (+)</td>
<td>-0.30 (0.04)***</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>[3] ML (-) to (=)</td>
<td>-0.07 (0.05)</td>
<td>0.05</td>
</tr>
<tr>
<td>[4] ML (=) to (+)</td>
<td>-0.11 (0.04)*</td>
<td>0.01</td>
</tr>
<tr>
<td>1:3</td>
<td>-0.12 (0.12)</td>
<td>0.15</td>
</tr>
<tr>
<td>1:4</td>
<td>0.08 (0.10)</td>
<td>0.45</td>
</tr>
<tr>
<td>2:3</td>
<td>0.03 (0.12)</td>
<td>0.63</td>
</tr>
<tr>
<td>2:4</td>
<td>-0.04 (0.10)</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Num. obs. 2340
Num. groups: Participant 26

***p < 0.001, **p < 0.01, *p < 0.05

Figure 4.2: Experiment 5 - Mean processing accuracy (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities from the model (see Table 4.3) are plotted over mean accuracy data.
4.4 Discussion

Using the same procedure as Experiment 3 (except for the substitution of a verbal memory task for the visual patterns task) had the desired effect of maintaining the memory load effect on memory performance. The analysis of memory accuracy also revealed a significant effect of processing load, but only for the PL(=)→PL(+) increase in load. This above-span effect of processing load was present across all memory load conditions (i.e. even for below-span lists). This suggests that either the resource responsible for performance on the processing task is also aiding maintenance of ‘at span’ and ‘below span’ lists, or that the increased number of errors in the PL(+) condition is having a disruptive effect. However, unlike in Experiment 4, the inclusion of the processing errors predictor did not remove the effect of load between the PL(=) and PL(+) conditions, suggesting separable and additive effects of each.

Analysing the effect of processing load across all tested values revealed an overall effect of the number of processing items in the maintenance interval (i.e. retrievals-per-second, RPS) (see Model A, Table 4.2). The effect of RPS was also larger between the ML(=) and ML(+) conditions (see the interaction labelled 2:RPS). However, the addition of the processing errors predictor to the model considerably reduced the effect of RPS to non-significance, including the interaction with memory load (although the coefficient estimate is unchanged and approached statistical significance).

The analysis of processing accuracy revealed an effect of memory load only for the ML(=)→ML(+) increase in load across all processing load levels (no interactions were detected).

Overall these results support our hypothesis that presenting participants with ‘above span’ lists results in a shared-resource effect between memory and processing
4.4. Discussion

tasks: both tasks are affected when the other task is set above participants’ measured single-task span. However, what we didn’t expect was that memory performance would also be affected for lists lengths below participants’ span (see Figure 4.1, page 105). In our discussion of Experiments 1 and 2 we suggested that measured single-task memory spans may already be artificially high due to some additional recruitment of attention, strategies, or refreshing (e.g. Logie et al., 1996; Camos et al., 2009, 2011). It is possible that attentional resources were being recruited in the single-task memory span condition, and that once the dual-task is introduced the additional load of co-ordinating two tasks is enough to disrupt memory performance when the processing task is set above participants’ span. Since a mirror effect is not observed in the analysis of processing accuracy (i.e. no effect of memory load between the ‘below span’ and ‘at span’ load conditions), it is possible that this ‘cost’ to memory performance is more related to a general dual-task cost as described by Duff and Logie (1999, 2001) rather than a general ‘cognitive load’ effect predicted by the TBRS model. The fact that the RPS effect is negated by the inclusion of the processing errors factor supports this.
Chapter 5

Dual-Task Verbal Memory &
Verbal Processing
5.1 Experiment 6

Introduction

Experiment 5 revealed above-span effects of spatial processing load on verbal memory accuracy for all list lengths, including below span lists. We interpreted this effect as being due to an additive cost of an involvement of attention in co-ordinating dual-tasking (as suggested Duff & Logie, 1999, 2001; Logie & Duff, 2007). The effect of above-span memory load on processing accuracy was suggested as being potentially due to some involvement of visual memory in the storage of lists exceeding participants’ verbal memory capacity.

Our previous experiments have included combinations of verbal and visual memory tasks with verbal and spatial processing tasks. In Experiment 2 the combination of a visual memory task and a spatial processing task resulted in a large effect on memory accuracy, but no effect of memory load on processing accuracy. This pattern was replicated in Experiment 3. Doherty and Logie’s (2016) investigation of verbal memory span found a significant effect of memory load on spatial processing, and this effect was replicated in Experiment 5 (although for the below-span to at-span increase in memory load, rather than at-span to above-span). Doherty and Logie (2016) found no effect of spatial processing on verbal memory span, although Figure 2.2 (page 45), suggests a small effect. Experiment 2 only found an effect of within domain (visuospatial) interference when the processing task was set two levels above participants’ span.

The within- and between-domain patterns of effects are clearly mixed in the previous experiments. In Chapter 2 we hypothesised that this may be due to lack of statistical power to detect small effects, and this interpretation was supported in later investigations that analysed trial-level data. In Chapter 3 we argued that
the mixed results were due to inherent difficulties of measuring visual memory with the visual patterns task due to the fact that it may be approached in a number of different ways (Brown et al., 2006; Brown & Wesley, 2013) that may not be conducive to successful dual-tasking, or clear patterns of data allowing interpretation of cross-task interference.

It therefore seems important to confirm that above-span effects of processing load on verbal memory are observed with a verbal processing task, and so Experiment 6 paired a verbal memory task with the lexical decision task described in Chapter 3. The clearer pattern of data facilitated by the use of a verbal memory task in Experiment 5 should result in clearer within-domain memory/processing trade-off effects in Experiment 6. While in Experiment 5 processing accuracy was only affected by the memory task when memory load was set above participants’ spans, the two verbal tasks should result in a greater overlap in resources and representations. This should facilitate a clearer distinction between when participants switch from relying on automated and relatively attention-free rehearsal and storage mechanisms, to attention-based mechanisms that are vulnerable to interference from a secondary task.
Method

Participants

Participants were recruited both from the University of Edinburgh Psychology Department’s Subject Pool for first year Psychology students, and through the University of Edinburgh Student and Graduate Employment (SAGE) Career Service. Participants were awarded course credit or paid an honorarium depending on how they were recruited. A total of 27 participants took part in the experiment (2 males and 25 females, mean age = 21.3, range = 18-26).

Apparatus and Procedure

The experiment was programmed in the E-Prime 2.0® environment and presented on a 15-inch LCD monitor set at a 1280×1024 pixel resolution and 60Hz refresh rate. Responses were collected via a keyboard with keys marked with a ‘tick’ and a ‘cross’. Both memory and processing stimuli were presented in a 18pt lower-case Arial font. Participants sat roughly 60cm from the computer monitor.

The procedure for the experiment was the same as that described in Chapter 4, except for the substitution of the speeded lexical decision task described in Experiment 4.
Results

Data from Experiment 6 were analysed using the same methods as described in Chapters 3 and 4. Mean single-task verbal memory span was 6.3 ($SD = 0.9$), and mean single-task verbal processing span was 6.7 ($SD = 1.0$).

Dual-Task Verbal Memory

Mean memory accuracies from each memory and processing load manipulation are shown in Figure 5.1. The effect of memory load on memory accuracy is unsurprising: participants recall smaller proportions of longer lists. Collapsed across processing load conditions, the unstandardised memory load effect sizes were -12.3% for $ML(-)\rightarrow ML(=)$ and -12.0% for $ML(=)\rightarrow ML(+)\ (95\%\ CI\ [-15.2\%,\ -9.7\%]$ and respectively).

Processing load effects were considerably smaller: collapsed across memory load conditions, the effect size between $PL(-)$ and $PL(=)$ loads was near-zero at -1.2% (95% CI[-4.8%, 1.8%]). The effect between $PL(=)$ and $PL(+)\ processing loads was slightly larger at -4.4% (95% CI[-7.0%, -1.9%]).

Processing Load. Table 5.1 displays coefficient estimates from Models A and B. The effect of increasing memory load is clear in both models for both $ML(-)\rightarrow ML(=)$ and $ML(=)\rightarrow ML(+)\). However, only the coefficient for the $PL(=)\rightarrow PL(+)\ increase in processing load is statistically significant. The significant interaction terms are easy to interpret when considered alongside Figure 5.1: the drop in recall accuracy between the $PL(=)$ and $PL(+)\ conditions is greater when memory is at span ($ML[=]\ condition$) compared to when it is below span ($ML[-]$). The lack of significant processing load interaction between the $ML(=)$ and $ML(+)\ conditions means that the $PL(-)\rightarrow PL(=)$ effect is the same for both ‘at span’ and ‘above span’ memory loads.
Interpreting the statistically significant coefficients in Model B in Table 5.1 in terms of the likelihood of giving a correct or incorrect response, participants were $\frac{1}{e^{-0.18}} = 1.82$ times more likely to produce an error in the ML(=) condition than in the ML(-) condition, and $\frac{1}{e^{-0.47}} = 1.60$ times more likely in the ML(+) condition. Memory task errors were $\frac{1}{e^{0.15}} = 1.16$ times more likely in the PL(+) condition than in the PL(=) condition. For the memory load:processing load interaction, participants were $\frac{1}{e^{-0.29}} = 1.34$ times more likely to produce a memory task error in the PL(+) condition when memory load was set at span (‘=’) compared to when it was set below span (‘-’). Due to the lack of processing load interaction between ML(=) and ML(+) conditions means that this is also true for the PL(=)→PL(+) increase. Also, for each error on the processing task participants were $\frac{1}{e^{-0.05}} = 1.05$ times more likely to produce an error on the memory task.
Table 5.1: Experiment 6 - Summary of ‘Processing Load’ Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>0.89 (0.11)***</td>
<td>0.96 (0.11)***</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>-0.61 (0.05)***</td>
<td>-0.60 (0.05)***</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>-0.47 (0.04)***</td>
<td>-0.47 (0.04)***</td>
</tr>
<tr>
<td>[3] PL (-) to (=)</td>
<td>-0.05 (0.05)</td>
<td>-0.03 (0.05)</td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>-0.19 (0.05)***</td>
<td>-0.15 (0.05)**</td>
</tr>
<tr>
<td>1:3</td>
<td>0.22 (0.13)</td>
<td>0.22 (0.13)</td>
</tr>
<tr>
<td>1:4</td>
<td>-0.28 (0.11)**</td>
<td>-0.29 (0.11)**</td>
</tr>
<tr>
<td>2:3</td>
<td>-0.18 (0.13)</td>
<td>-0.18 (0.13)</td>
</tr>
<tr>
<td>2:4</td>
<td>0.10 (0.10)</td>
<td>0.10 (0.10)</td>
</tr>
<tr>
<td>ProcErrors</td>
<td></td>
<td>-0.05 (0.02)**</td>
</tr>
<tr>
<td>AIC</td>
<td>9102.36</td>
<td>9094.80</td>
</tr>
<tr>
<td>BIC</td>
<td>9160.32</td>
<td>9158.55</td>
</tr>
<tr>
<td>Log Likelihood</td>
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<td>-4536.40</td>
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<td>Num. obs.</td>
<td>2430</td>
<td>2430</td>
</tr>
<tr>
<td>Num. groups: Participant</td>
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<td>27</td>
</tr>
</tbody>
</table>

***p < 0.001, **p < 0.01, *p < 0.05

Figure 5.1: Experiment 6 - Mean memory accuracy (with bootstrapped confidence intervals) across each combination of memory load and processing load (PL). Predicted probabilities from Model B (see Table 5.1) are plotted over mean accuracy data.
**Retrieval-per-second (RPS).** The results of the RPS analyses are shown in Table 5.2. Both models contain significant effects of memory load (identical to those observed in the analysis of processing load) and of RPS, and memory load:RPS interactions between the ML(=) and ML(+) conditions.

Model B features a significant effect of processing errors. Although there is a statistically significant effect of RPS, this effect is driven by the large effect of RPS in the ML(+) condition, and indeed there is a significant interaction between memory load and RPS for the ML(=)→ML(+) contrast. A cursory comparison of the RPS coefficients in Models A and B shows that the effect is reduced with the introduction of the processing errors variable, yet remains statistically significant.

Interpreting the RPS coefficient in Model B, participants were $\frac{1}{e^{-0.34}} = 1.40$ times more likely to produce a memory task error with each increase in RPS. For the interaction, participants were $\frac{1}{e^{-0.43}} = 1.54$ times more likely to produce an error with each increase in RPS in the ML(+) condition than in the ML(=) condition, compared to the difference between the ML(-) and ML(+) conditions. The processing error effect was the same as in the analysis of processing load ($\frac{1}{e^{-0.05}} = 1.05$).
Table 5.2: Experiment 6 - Summary of RPS Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>0.89 (0.11)**</td>
<td>0.97 (0.11)**</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>-0.60 (0.05)**</td>
<td>-0.60 (0.05)**</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>-0.47 (0.04)**</td>
<td>-0.46 (0.04)**</td>
</tr>
<tr>
<td>RPS</td>
<td>-0.52 (0.11)**</td>
<td>-0.34 (0.13)**</td>
</tr>
<tr>
<td>1:RPS</td>
<td>0.04 (0.20)</td>
<td>0.05 (0.20)</td>
</tr>
<tr>
<td>2:RPS</td>
<td>-0.43 (0.16)**</td>
<td>-0.43 (0.16)**</td>
</tr>
<tr>
<td>ProcErrors</td>
<td></td>
<td>-0.05 (0.02)**</td>
</tr>
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<td>AIC</td>
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<td>9096.32</td>
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<tr>
<td>BIC</td>
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</tr>
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<td>-4540.16</td>
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<td>27</td>
</tr>
</tbody>
</table>

***p < 0.001, **p < 0.01, *p < 0.05, p < 0.1
Dual-Task Verbal Processing.

Figure 5.2 displays mean processing accuracy across memory load and processing load conditions. Collapsed across memory load conditions, the unstandardised processing load effect sizes were 5.9% for PL(-) → PL(=) and 8.5% for PL(=) → PL(+) (95% CIs [4.1%, 7.7%] and [6.6%, 10.7%] respectively). Unstandardised memory load effect sizes were 1.1% for ML(-) → ML(=) and 1.7% for the ML(=) → ML(+) (95% CIs [-0.5%, 2.5%] and [-0.2%, 3.5%]).

**Memory Load.** Table 5.3 summarises the regression analysis, and reveals a statistically significant coefficient for each increase in processing load. Participants were $\frac{1}{e^{0.45}} = 1.57$ times more likely to make an error in the PL(=) condition compared to the PL(-) condition, and $\frac{1}{e^{0.48}} = 1.62$ times more likely in the PL(+) condition. The model contains a significant coefficient for the ML(-) → ML(=) increase in memory load, but not the ML(=) → ML(+) increase. However, the coefficients for both these memory load comparisons are nearly identical, and the p-value for the latter comparison is near-statistically significant ($p = 0.51$). These coefficients translate to a $\sim \frac{1}{e^{0.11}} = 1.12$ increase in the probability of making an error on the processing task with each increase in memory load.

**Reaction Time.** Vergauwe et al. (2014) reported an effect of verbal memory load on processing reaction time (RT). Participants were slower at responding to processing items (judging whether a number presented on screen was ‘even’ or ‘odd’) as list length increased. This effect was most robust for the first processing item compared to subsequent processing items (analysed separately). We analysed our data in the similar way via hierarchical linear regression analysis of first-item and subsequent item RT (these data are summarised in Figure 5.3). We assume that non-responses occur when participants are unable to answer trials before the next
item is presented, and as such attention was engaged for the full duration of the item presentation. For this reason RTs for non responses were recorded as 100% of the time the processing item was on screen. Therefore, to avoid spurious effects, trials with no responses were removed from the ‘First RT’ analysis. Non-response trials were kept in for the ‘Subsequent RT’ analysis as removing trials where any one of the processing items was not responded to resulted in a large number of exclusions. Reaction times < 250ms were also removed from the analyses as they had been in Experiment 1. The results from these analyses are summarised in Table 5.4. Alongside the predictable effect of processing load on RTs in both analyses, there was a clear effect of memory load on first-item RTs but no effect on the RTs for subsequent processing. There were no significant interactions in either analysis.
Figure 5.2: Experiment 6 - Mean processing accuracy (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities calculated from the coefficient estimates in Table 5.3 are plotted over mean accuracy data.

Table 5.3: Experiment 6 - Summary of ‘Memory Load’ Logistic Regression on Processing Accuracy

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
</tr>
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<td>(Intercept)</td>
<td>1.46 (0.11)***</td>
</tr>
<tr>
<td>[1] PL (-) to (=)</td>
<td>-0.45 (0.06)***</td>
</tr>
<tr>
<td>[2] PL (=) to (+)</td>
<td>-0.48 (0.04)***</td>
</tr>
<tr>
<td>[3] ML (-) to (=)</td>
<td>-0.11 (0.05)*</td>
</tr>
<tr>
<td>[4] ML (=) to (+)</td>
<td>-0.10 (0.05)</td>
</tr>
<tr>
<td>1:3</td>
<td>0.12 (0.14)</td>
</tr>
<tr>
<td>1:4</td>
<td>-0.09 (0.11)</td>
</tr>
<tr>
<td>2:3</td>
<td>0.12 (0.13)</td>
</tr>
<tr>
<td>2:4</td>
<td>-0.00 (0.11)</td>
</tr>
</tbody>
</table>

Num. obs. 2430
Num. groups: Participant 27

***p < 0.001, **p < 0.01, *p < 0.05
Figure 5.3: Experiment 6 - Mean verbal processing reaction times for the first items (a) and subsequent items (b) (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities calculated from the coefficient estimates in Table 5.4 are plotted over mean accuracy data.
Table 5.4: Experiment 6 - Summary of Reaction Time Linear Regression Models

<table>
<thead>
<tr>
<th></th>
<th>First RTs</th>
<th>Subsequent RTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>622.60 (16.16)**</td>
<td>512.36 (10.26)**</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>13.64 (5.16)**</td>
<td>-2.46 (3.65)</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>20.36 (5.20)**</td>
<td>-5.07 (3.65)</td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>-44.41 (5.32)**</td>
<td>-51.66 (3.65)**</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>First RTs</th>
<th>Subsequent RTs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-12.70 (12.50)</td>
<td>-4.27 (8.93)</td>
</tr>
<tr>
<td>1:3</td>
<td>5.06 (12.57)</td>
<td>-5.76 (8.93)</td>
</tr>
<tr>
<td>1:4</td>
<td>-15.25 (12.78)</td>
<td>-7.80 (8.93)</td>
</tr>
<tr>
<td>2:3</td>
<td></td>
<td>-1.98 (8.93)</td>
</tr>
<tr>
<td>2:4</td>
<td>3.59 (12.86)</td>
<td></td>
</tr>
</tbody>
</table>

Num. obs. | 2194 | 2430 |
Num. groups | 27 | 27 |

***p < 0.001, **p < 0.01, *p < 0.05
5.1. Experiment 6

Discussion

The experimental manipulation of increasing concurrent verbal processing load resulted in a relatively small drop in memory performance, especially when compared to the effect of increasing list length. This effect of processing load was only present for the ‘at span’ to ‘above span’ (PL[=]→PL[+]) increase, and only in the ‘at span’ and ‘above span’ (ML[=] and ML[+]) memory load conditions: processing load had no effect on memory accuracy in the ‘below span’ memory load condition (ML[-]).

The RPS analysis revealed a similar pattern of results: participants’ memory performance was only affected by the demand of the processing task when memory load was set above span (evident in the ML[=]→ML[+]:RPS interaction, labelled 2:RPS in Table 5.2, page 119).

The results of these analyses support the hypothesis that the load of both tasks affect participants’ dual-tasking ability. In the analysis of processing load, the titrated demand of the processing task only affected memory accuracy when memory was set at participants’ single-task memory span or above, and when processing load was set above single-task processing span. Figure 5.1 also suggests that memory accuracy is slightly higher when both tasks are set at span.\footnote{It is possible that when both tasks are set at span there is some increased competition and participants were prioritising the memory task over the processing task in order to ‘boost’ performance. Task prioritisation is investigated in Chapter 6.}

The RPS regression analysis also includes this interaction effect, as memory accuracy is negatively affected by processing load when list length is above span. We argue that this is due to some involvement of attentional resources in the support of default phonological maintenance mechanisms (similar to the ‘adaptive choice’ described by Camos & Barrouillet, 2014): participants were able to perform both processing and storage simultaneously when the rehearsal via the phonological loop is viable (i.e. at shorter list lengths), but dual-task performance breaks down once the loop’s capacity is
exceeded and other rehearsal mechanisms are recruited.

Separating the effect of processing load from the effect of increased secondary task error rates and identifying the true source of interference is difficult. In the processing load analysis (Table 5.1, page 117), the inclusion of the processing errors variable slightly reduced the size of the $PL(=)-PL(+)\text{ coefficient. This reduction is greater in the analysis of retrievals-per-second (RPS) across all tested values (Table 5.2, page 119).}$ A approximate comparison of the RPS and processing errors coefficients reveals that the effect of making a single error results in an equivalent drop in performance across all RPS values. This suggests that errors play a much larger role in memory disruption than the demand of the processing task, in line with the findings of Lewandowsky and Oberauer (2009). It could be argued that it is not the involvement of a domain-general resource in the maintenance of above span memory loads that results in the effects described above, but that the disruptive nature of errors is more exaggerated when the multiple components of a working memory system are under high load.

It is therefore important to consider the effect of memory load on processing. The analysis of processing accuracy revealed significant and marginally significant coefficients for each subsequent increase in memory load ($ML[-]-ML[=] p = .04$, $ML(=)-ML[+] p = .05$). The small coefficients do not support a direct trade-off of processing resources towards the support of maintenance of memory items, as increasing memory beyond participants’ single-task span does not result in a clear drop in processing accuracy. The reaction time analysis for first processing items did reveal a significant effect of memory load, replicating Vergauwe et al.’s (2014) finding that participants were slower to respond to the first processing item when under high memory load. This coefficient was larger for the change in memory load between the $ML(=)-ML(+)\text{ conditions, but this is due to the lack of effect between ML(-)}$ and
ML(=) conditions when processing load was above span (see Figure 5.3a). We did not find a significant effect of memory load on subsequent RTs, which may be due to differences between our procedure and that of Vergauwe et al., whose processing task was participant-paced and so allowed for more variation in reaction times than our experiment-paced task. Also, their largest effects were in AS conditions, with smaller effects in the non-suppression conditions. The procedure for Experiment 6 did not include any AS, meaning that participants were free to rehearse items phonologically and so were less likely to rely on other attention-based rehearsal mechanisms.

It is important to note that although our procedures differed from those of Vergauwe et al. we find little evidence for an effect of memory load on processing speed. Indeed Vergauwe et al. (paper’s Experiment 6) reported small effects of memory load on processing speed in the non-suppression experiment, and only for list lengths > 4 items. The fact that we so clearly replicate the memory load effect for first processing items but not subsequent items is surprising, especially since our list lengths far exceed those used in Vergauwe et al.. A possible explanation for the mechanisms and processes involved in maintenance of above span lists could be that some extra time is spent encoding memory items, and that this encroaches on the response time of the first item in the processing list. Whether this is some form of attentional refreshing as described in the TBRS model, encoding/orienting long-term memory (Cowan, 2005), a form of visual recoding (e.g. Saito et al., 2008), transfer to ‘secondary memory’ (e.g. Unsworth & Engle, 2007), or the use of some other strategy (e.g. Logie et al., 1996), we would expect to detect a different pattern of memory and processing performance if the presentation time of memory items was shortened.

The observed effect of memory load on reaction times for the first processing items supports our own hypothesis, and the conclusions of Vergauwe et al. (2014)
and Camos and Barrouillet (2014), that maintenance processes can involve the same attentional resource as processing tasks. Whether the reason the effect of memory load on processing RT was limited to first item responses was due to the fact that participants were allowed a long encoding phase was investigated in Experiment 7.
5.2 Experiment 7: + Shorter presentation of memory items

Introduction

Experiment 6 revealed no effect of processing load on memory accuracy when the processing task was set below span. Likewise, no effect of memory load on processing accuracy was observed, but a significant effect of memory load was found for the speed at which participants responded to the first processing items. Since no effect of memory load was observed for subsequent processing reaction times, both tasks appear to be independent during the majority of the processing phase.

We interpret this as a separation of maintenance from concurrent verbal processing (as reported by Duff & Logie, 1999), with the effect of processing load on memory performance being limited to when the lexical decision task is set above participants’ measured single-task ability.

The procedure for Experiment 6 allowed participants considerable time to study the memory items, with letters being presented simultaneously for 1000ms per item. If participants are supplementing domain-specific memory resources (e.g. the phonological loop) with other rehearsal or maintenance methods, such as attentional refreshing or visual recoding, the effect of memory load on response times for the first processing items could be due to the time it takes to activate these additional mechanisms. Naveh-Benjamin and Jonides (1984) reported an effect of rehearsal on secondary task reaction time using a procedure that encouraged the use of multiple rehearsal strategies (participants spoke list items out loud as well as being instructed to visualise the items in order to improve performance). If the effect of memory load on processing task reaction time was limited to the first processing items because of the extra effort to recruit additional maintenance mechanisms for longer lists, short-
eneng the time available for encoding may encroach upon subsequent processing and affect RTs.

Alternatively, a shortened encoding phase may result in insufficient time to recruit additional resources for short term memory storage, meaning that participants are required to rehearse using default phonological mechanisms. This should result in a complete separation of the tasks during dual-tasking, with less interference (i.e. no cost of contra-task load effect on memory or processing) than that observed in Experiment 6.

Experiment 7 investigated possible effects of encoding/activation of rehearsal mechanisms by reducing the presentation time for memory items.
Method

Participants, Materials, & Procedure

Participants were recruited in the same way as in Experiment 6, resulting in the following sample: $n = 27$ (4 males, 23 females), mean age = 22.9, range = 19-27. The materials and procedure were also the same as in Experiment 6, except for a change in the timing of the presentation of memory items. Whilst in Experiment 6 the list of memory items appeared for $m \times 1000\text{ms}$ (where $m$ = the number of memory items), in this experiment this time was shortened to $m \times 500\text{ms}$. 
5.2. Experiment 7: + Shorter presentation of memory items

Results

Mean single-task verbal memory span was 5.8 ($SD = 0.8$), and mean single-task verbal processing span was 6.8 ($SD = 1.4$).

Dual-task Verbal Memory

Mean memory accuracy data are shown in Figure 5.4. Collapsed across processing load conditions, the unstandardised memory load effect sizes were -8.9% for ML(-)$\rightarrow$ML(=) and -12.9% for ML(=)$\rightarrow$ML(+) (95% CIs[-11.0%, -7.0%] and [-16%, -10.0%] respectively). Processing load effect sizes were -3.6% between PL(-) and PL(=), and -0.3% between PL(=) and PL(+) (95% CIs[-5.7%, -1.7%] and [-3.0%, 2.1%] respectively).

Processing Load Trial-level data were analysed as described in Experiment 6. The results of the regression analyses are shown in Table 5.5. Model A contains a statistically significant coefficient for the PL(-)$\rightarrow$PL(=) increase in processing load, which appears to be driven by a larger effect in the PL(+) conditions compared to other memory load conditions. Once processing task errors are controlled for in Model B, the negative effect is no longer statistically significant between PL(-)$\rightarrow$PL(=) and instead is positive between PL(=)$\rightarrow$PL(+) processing loads.

Interpreting the statistically significant coefficients in Model B in Table 5.5 in terms of the likelihood of giving a correct or incorrect response, participants were $\frac{1}{e^{-0.54}} = 1.72$ times more likely to produce an error in the ML(=) condition compared to the ML(-) condition, and $\frac{1}{e^{-0.56}} = 1.75$ times more likely in the ML(+) condition. In Model A, participants were $\frac{1}{e^{-0.13}} = 1.14$ times more likely to make a memory task error in the PL(=) condition compared to the PL(-) condition, but this effect was not significant in Model B. In Model B (when processing task errors were controlled for) participants were $e^{0.14} = 1.15$ times more accurate in the memory task in the
PL(+) condition than in the PL(-) condition, after memory load effects are taken into account. Again, in Model B, for every error made in processing task, participants were $e^{1.16} = 1.17$ times more likely to produce a memory task error.
5.2. Experiment 7: + Shorter presentation of memory items

Table 5.5: Experiment 7 - Summary of ‘Processing Load’ Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.26 (0.12)***</td>
<td>1.53 (0.12)***</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>−0.56 (0.06)***</td>
<td>−0.54 (0.06)***</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>−0.58 (0.05)***</td>
<td>−0.56 (0.05)***</td>
</tr>
<tr>
<td>[3] PL (-) to (=)</td>
<td>−0.13 (0.06)*</td>
<td>−0.02 (0.06)</td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>−0.02 (0.05)</td>
<td>0.14 (0.06)*</td>
</tr>
<tr>
<td>1:3</td>
<td>−0.06 (0.15)</td>
<td>−0.06 (0.15)</td>
</tr>
<tr>
<td>1:4</td>
<td>−0.12 (0.12)</td>
<td>−0.12 (0.12)</td>
</tr>
<tr>
<td>2:3</td>
<td>0.14 (0.14)</td>
<td>0.17 (0.15)</td>
</tr>
<tr>
<td>2:4</td>
<td>0.03 (0.12)</td>
<td>0.01 (0.12)</td>
</tr>
<tr>
<td>ProcErrors</td>
<td>−0.16 (0.02)***</td>
<td>−0.16 (0.02)***</td>
</tr>
</tbody>
</table>

AIC 7600.07 7502.83
BIC 7658.03 7566.59
Log Likelihood −3790.04 −3740.42
Num. obs. 2430 2430
Num. groups: Participant 27 27

***p < 0.001, **p < 0.01, *p < 0.05

Figure 5.4: Experiment 7 - Mean memory accuracy (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities from Model B (see Table 5.5) are plotted over mean accuracy data.
5.2. Experiment 7: + Shorter presentation of memory items

Table 5.6: Experiment 7 - Summary of RPS Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.26 (0.12)***</td>
<td>1.53 (0.12)***</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>-0.56 (0.06)***</td>
<td>-0.54 (0.06)***</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>-0.58 (0.05)***</td>
<td>-0.56 (0.05)***</td>
</tr>
<tr>
<td>RPS</td>
<td>-0.30 (0.13)*</td>
<td>0.35 (0.14)*</td>
</tr>
<tr>
<td>1:RPS</td>
<td>-0.14 (0.19)</td>
<td>-0.07 (0.19)</td>
</tr>
<tr>
<td>2:RPS</td>
<td>-0.08 (0.15)</td>
<td>-0.14 (0.15)</td>
</tr>
<tr>
<td>ProcErrors</td>
<td></td>
<td>-0.16 (0.02)***</td>
</tr>
<tr>
<td>AIC</td>
<td>7599.92</td>
<td>7502.57</td>
</tr>
<tr>
<td>BIC</td>
<td>7640.48</td>
<td>7548.94</td>
</tr>
<tr>
<td>Log Likelihood</td>
<td>-3792.96</td>
<td>-3743.29</td>
</tr>
<tr>
<td>Num. obs.</td>
<td>2430</td>
<td>2430</td>
</tr>
<tr>
<td>Num. groups: Participant</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

***p < 0.001, **p < 0.01, *p < 0.05, p < 0.1

**Retrievals-per-second (RPS)** The effect of RPS was investigated in the same way as in Experiment 6. The results from these analyses are shown in Table 5.6. Model A contains a significant negative coefficient for RPS. However, with the inclusion of the processing errors variable in Model B this effect is positive (both coefficients translate to a $\sim 1.38$ increase in accuracy/errors respectively). This suggests that RPS alone is a poor predictor of performance across all participants, as participants in high RPS conditions (i.e. participants who demonstrated a higher single-task processing span) perform better than participants in lower RPS conditions. It is important to note that this is only the case when the number of processing task errors is 0 as coefficient estimates are based on other values being set at 0.
5.2. Experiment 7: + Shorter presentation of memory items

Dual-Task Verbal Processing

Collapsed across memory load conditions, the unstandardised processing load effect sizes were -7.5% for PL(-) → PL(=) and -9.2% for PL(=) → PL(+) (95% CIs [-9.7%, -5.4%] and [-12.2%, -6.6%] respectively). Unstandardised memory load effect sizes were -2.3% for ML(-) → ML(=) and -3.3% for the ML(=) → ML(+) (95% CIs [-3.9%, -1.0%] and [-5.5%, -1.3%]).

Memory Load. Dual-task verbal processing performance was analysed using the same procedure as Experiment 6. Mean processing accuracy across processing and memory load conditions are shown in Figure 5.5, and coefficient estimates are summarised in Table 5.7. The model contains statistically significant effects of both processing and memory load, but no interaction effects. Processing errors were $\frac{1}{e^{0.54}} = 1.72$ times more probably in the PL(=) condition compared to the PL(-) condition, and $\frac{1}{e^{0.72}} = 1.67$ times more probable in the PL(+) condition. For the memory load increases, participants were $\frac{1}{e^{0.16}} = 1.17$ times more likely to make an error in the ML(=) condition than in the ML(-) condition, and $\frac{1}{e^{0.17}} = 1.19$ times more likely in the ML(+) condition.

Reaction Time. As with Experiment 6, RTs were analysed via hierarchical linear regression (data and analyses summarised in Figure 5.6 and Table 5.8). The analyses revealed a significant effect of memory load on reaction time for the first processing items, but no effect of memory load on subsequent RTs. The regression analysis of first item RTs also revealed a significant interaction between the ML(-) → ML (=) and PL(=) → PL(+) conditions, which reflects the overlapping datapoints in the ML(-) condition in Figure 5.6a.
Figure 5.5: Experiment 7 - Mean processing accuracy (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities calculated from the coefficient estimates in Table 5.7 are plotted over mean accuracy data.

Table 5.7: Experiment 7 - Summary of Logistic Regressions on Processing Accuracy

| Model 1 |  
| (Intercept) | 1.33 (0.10)**
| [1] PL (-) to (=) | -0.54 (0.05)***
| [2] PL (=) to (+) | -0.51 (0.04)***
| [3] ML (-) to (=) | -0.16 (0.05)**
| [4] ML (=) to (+) | -0.17 (0.05)***
| 1:3 | -0.03 (0.13)
| 1:4 | 0.04 (0.11)
| 2:3 | 0.06 (0.13)
| 2:4 | 0.06 (0.10)

Num. obs. 2430
Num. groups: Participant 27

***p < 0.001, **p < 0.01, *p < 0.05
5.2. Experiment 7: + Shorter presentation of memory items

Figure 5.6: Experiment 7 - Mean verbal processing reaction times for the first items (a) and subsequent items (b) (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities calculated from the coefficient estimates in Table 5.8 are plotted over mean accuracy data.
Table 5.8: Experiment 7 - Summary of Reaction Time Linear Regression Models

<table>
<thead>
<tr>
<th></th>
<th>First RTs</th>
<th>Subsequent RTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>617.67 (13.18)**</td>
<td>514.30 (13.57)**</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>25.97 (4.82)**</td>
<td>0.64 (3.58)</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>16.16 (4.87)**</td>
<td>-3.73 (3.58)</td>
</tr>
<tr>
<td>[3] PL (-) to (=)</td>
<td>-23.85 (4.83)**</td>
<td>-34.20 (3.58)**</td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>-48.90 (5.05)**</td>
<td>-63.70 (3.58)**</td>
</tr>
<tr>
<td>1:3</td>
<td>-16.55 (11.69)</td>
<td>5.65 (8.76)</td>
</tr>
<tr>
<td>1:4</td>
<td>-26.63 (11.79)*</td>
<td>-13.93 (8.76)</td>
</tr>
<tr>
<td>2:3</td>
<td>5.10 (12.06)</td>
<td>-2.92 (8.76)</td>
</tr>
<tr>
<td>2:4</td>
<td>0.26 (12.22)</td>
<td>-11.35 (8.76)</td>
</tr>
</tbody>
</table>

Num. obs.          2174  2430
Num. groups        27   27

***p < 0.001, **p < 0.01, *p < 0.05
5.2. Experiment 7: + Shorter presentation of memory items

Discussion

Experiment 7 provided little evidence for an effect of processing task load on memory accuracy. The experimental manipulation of processing load revealed small negative and positive effects of processing load, with processing errors remaining the best predictor of memory performance. Likewise the retrievals-per-second (RPS) analysis provided little evidence for a processing load effect across all values but a large effect of errors on memory accuracy.

These results would suggest that, compared to Experiment 6, participants are relying on a method of rehearsal that can operate with little interference from the processing task. The disruptive effect of processing errors remains, and baseline single-task performance is lower, but overall participants perform very well in the dual-task condition.

However, whereas in Experiment 6 processing accuracy was largely unaffected by concurrent memory load, a statistically significant effect was detected in Experiment 7. RTs for the first processing items were also affected by memory load (as in Experiment 6, subsequent RTs were not affected). While the differences in memory performance between these two experiments is clear when comparing Figures 5.1 (page 117) and 5.4 (page 134), the processing accuracy data patterns summarised in Figures 5.2 (page 122) and 5.5 (page 137) appear quite similar despite the differences in statistically significant effects between the two experiments. The small effect of memory load on processing accuracy in both experiments (see Tables 5.3 and 5.7 on pages 122 and 137), coupled with the fact that processing performance overall remains relatively high in the dual-task conditions compared to memory performance, suggest that the lack of effect of memory load on processing in Experiment 7 is due insensitivity of the statistical test due to both small effects and near-ceiling
performance in the processing task.²

As mentioned above, participants’ single-task memory span was lower in Experiment 7 than in Experiment 6. However, comparing Figures 5.1 and 5.4 (pages 117 & 134) it is also clear that dual-task memory accuracy was higher in Experiment 7 compared to Experiment 6. Assuming that the shorter presentation time for memory items predisposes participants to rely on more automated forms of storage and rehearsal, and that memory performance can be supported by other rehearsal methods besides those facilitated by domain-specific resources, then the longer encoding phase in Experiment 6 may have allowed participants to support their verbal memory storage and rehearsal with attention-based refreshing which resulted in artificially high memory spans. Allowing participants time to recruit these additional rehearsal resources during single-task results in memory span levels too high for successful dual-tasking (especially in the ‘above span’ condition), leading to poorer dual-task memory performance.

If shortening the presentation time for memory items causes participants to rely on more automatic or practised rehearsal methods that do not require attention and so lead to successful dual-tasking, then encouraging the use of attention-based rehearsal methods should result in poorer dual-task memory performance and increased processing load effects than observed in Experiments 6 and 7. This was the focus of Experiment 8.

²Indeed, when the effect of memory load on processing accuracy was tested across all experiments, no between-experiment interaction effects on processing accuracy were observed (see Section 5.4 on page 156).
5.3 Experiment 8: + Articulatory suppression

Introduction

The shorter presentation time in Experiment 7 resulted in lower single-task memory spans than Experiment 6, but also reduced the already small effect of processing task load on dual-task memory performance observed in the latter experiment. Assuming a flexible working memory system, with both domain-general and specialised procedures for verbal rehearsal (e.g. Logie, 2011; Camos & Barrouillet, 2014; Vergauwe et al., 2014), we hypothesise that the different patterns of data from these two experiments are due to participants’ reliance on different mechanisms for rehearsal (or at least using these mechanisms to different degrees). The higher single-task spans observed in Experiment 6 result from participants ‘boosting’ their verbal capacity with additional resources - an approach which results in poorer overall dual-task performance compared to participants in Experiment 7 as well as above-span processing load effects due to competition for the same resource responsible for verbal processing.

Experiment 8 aimed to increase participants’ reliance on attention-based rehearsal by introducing AS to the procedure of Experiment 6. By removing access to the phonological loop participants’ single-task performance should be lower (as was observed in Experiment 7), but we also expect an effect of concurrent processing task load on memory accuracy across all memory load levels.
5.3. Experiment 8: + Articulatory suppression

Method

Participants, Materials, & Procedure

Participants were recruited in the same way as in Experiments 6 and 7, resulting in the following sample: \( n = 27 \) (7 males, 20 females), mean age = 21.5, range = 18-26. The materials and procedure were also the same as in Experiment 6, except for the introduction of AS. In both the single- and dual-task conditions participants were instructed to repeat “ba ba ba ba...” at a speed of two repetitions per second from before the onset of the memory items and to continue throughout the 6000ms filled/unfilled retention interval. Participants were instructed to halt articulatory suppression during the ‘Recall’ screen. Participants’ practised AS with a metronome beforehand, and were prompted to speed up/slow down by the experimenter if they were not keeping to a consistent pace.
5.3. Experiment 8: + Articulatory suppression

Results

Mean single-task verbal memory span was 5.07 ($SD = 0.92$), and mean single-task verbal processing span was 6.22 ($SD = 1.34$).

Dual-task Verbal Memory

Mean memory accuracies from each memory and processing load manipulation are shown in Figure 5.7. Collapsed across processing load conditions, the unstandardised memory load effect sizes were -8.7% for ML(-)→ML(=) and -12.3% for ML(=)→ML(+) (95% CIs[-4.7%, -1.2%] and [-16.7%, -8.4%] respectively). Processing load effect sizes were -5.7% between PL(-) and PL(=), and -9.2% between PL(=) and PL(+) (95% CIs[-7.6%, -3.7%] and [-11.1%, -7.3%] respectively). The larger effect of processing load is clear when compared to Figure 5.1 (page 117) from Experiment 6.

Processing Load. Models A and B (Table 5.9) contain significant coefficients for both the PL(-)→PL(=) and PL(=)→PL(+) increases in processing load. Both models also contain a significant interaction at the PL(-)→PL(+) increase in processing between ML(-) and ML(+) conditions, fitting with the summary of the data shown in Figure 5.7. As observed in previous experiments, Model B also contained a significant effect of processing errors.

Interpreting the statistically significant coefficients in Model B in Table 3.1 in terms of the likelihood of giving a correct or incorrect response, errors were $\frac{1}{e^{0.39}} = 1.48$ more probable in the ML(=) condition compared to the ML(-) condition, and $\frac{1}{e^{0.46}} = 1.58$ more probable in the ML(+) condition. For processing load, participants were $\frac{1}{e^{0.47}} = 1.12$ times more likely to produce memory task errors in the PL(=) condition compared to the PL(-) condition, and $\frac{1}{e^{0.77}} = 1.15$ more likely in the PL(+) condition. For the memory load interaction labelled 1:3 in Table 5.9, participants were $\frac{1}{e^{-0.32}} = 1.38$ times more likely to make a processing
error in the PL(=) processing load condition when memory load was at span (‘=’) compared to when memory load was below span (‘-’) (on top of the main memory processing load effects). Conversely, for the interaction labelled 2:4, participants were $e^{0.25} = 1.28$ times more accurate when both tasks were set above span (after the general effect of memory and processing loads are taken into account). For each error in the processing task, participants were $\frac{1}{e^{-0.08}} = 1.08$ times more likely to produce an error in the memory task.
Table 5.9: Experiment 8 - Summary of ‘Processing Load’ Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>0.40 (0.11)***</td>
<td>0.50 (0.11)***</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>−0.39 (0.05)***</td>
<td>−0.39 (0.05)***</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>−0.46 (0.05)***</td>
<td>−0.46 (0.05)***</td>
</tr>
<tr>
<td>[3] PL (-) to (=)</td>
<td>−0.14 (0.05)**</td>
<td>−0.11 (0.05)*</td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>−0.21 (0.05)***</td>
<td>−0.14 (0.05)**</td>
</tr>
<tr>
<td>1:3</td>
<td>−0.34 (0.13)**</td>
<td>−0.32 (0.13)*</td>
</tr>
<tr>
<td>1:4</td>
<td>−0.03 (0.11)</td>
<td>−0.04 (0.11)</td>
</tr>
<tr>
<td>2:3</td>
<td>0.15 (0.13)</td>
<td>0.14 (0.13)</td>
</tr>
<tr>
<td>2:4</td>
<td>0.24 (0.11)*</td>
<td>0.25 (0.11)*</td>
</tr>
<tr>
<td>ProcErrors</td>
<td></td>
<td>−0.08 (0.02)***</td>
</tr>
</tbody>
</table>

AIC                   8804.22                     8787.21
BIC                   8862.18                     8850.96
Log Likelihood         −4392.11                    −4382.60
Num. obs.              2430                        2430
Num. groups: Participant 27                        27

***p < 0.001, **p < 0.01, *p < 0.05

Figure 5.7: Experiment 8 - Mean memory accuracy (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities from Model B (see Table 5.9) are plotted over mean accuracy data.
### Table 5.10: Experiment 8 - Summary of RPS Logistic Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>0.40 (0.11)**</td>
<td>0.49 (0.11)**</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>-0.39 (0.05)**</td>
<td>-0.39 (0.05)**</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>-0.46 (0.05)**</td>
<td>-0.47 (0.05)**</td>
</tr>
<tr>
<td>RPS</td>
<td>-0.87 (0.12)**</td>
<td>-0.63 (0.13)**</td>
</tr>
<tr>
<td>1:RPS</td>
<td>-0.25 (0.18)</td>
<td>-0.24 (0.18)</td>
</tr>
<tr>
<td>2:RPS</td>
<td>0.46 (0.15)**</td>
<td>0.46 (0.15)**</td>
</tr>
<tr>
<td>ProcErrors</td>
<td></td>
<td>-0.07 (0.02)**</td>
</tr>
<tr>
<td>AIC</td>
<td>8804.39</td>
<td>8787.88</td>
</tr>
<tr>
<td>BIC</td>
<td>8844.96</td>
<td>8834.24</td>
</tr>
<tr>
<td>Log Likelihood</td>
<td>-4395.20</td>
<td>-4385.94</td>
</tr>
<tr>
<td>Num. obs.</td>
<td>2430</td>
<td>2430</td>
</tr>
<tr>
<td>Num. groups: Participant</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

***p < 0.001, **p < 0.01, *p < 0.05, p < 0.1

**Retrievals-per-second (RPS)** Models A and B both contain statistically significant coefficients for RPS: participants were \( \frac{1}{e^{0.87}} = 2.39 \) times more likely to make a memory error with each increase in RPS in Model A, and \( \frac{1}{e^{0.63}} = 1.88 \) times more likely in B. The effect of RPS was reduced in Model B once the number of processing errors is controlled for, with each error having the same effect on the probability of producing an error as observed in the analysis of processing load. Both models also contain a significant interaction coefficient for the ML(=)→ML(+):RPS interaction, however this coefficient is positive meaning that participants were \( e^{0.46} = 1.58 \) times more accurate on the memory task with each increase in RPS in the ML(+) condition once the large effects of memory load and RPS are accounted for. This is most likely due to the fact that memory performance is considerably poorer under articulatory suppression (compare Figure 5.7 with Figure 5.1) making it difficult to detect RPS in the high memory load condition due to performance being poorer at even low RPS levels. The effect of processing errors was the same as observed in the processing load analysis, with participants being \( \frac{1}{e^{-0.07}} = 1.07 \) times more likely to
5.3. Experiment 8: + Articulatory suppression

produce an error in the memory task with each additional error on the processing task.
Dual-Task Verbal Processing

Figure 5.8 displays mean verbal processing accuracy across processing load (PL) and memory load (ML) conditions. Collapsed across memory load conditions, the unstandardised processing load effect sizes were 5.7% for PL(-)→PL(=) and 9.2% for PL(=)→PL(+) (95% CIs [3.7%, 7.7%] and [7.3%, 11.3%] respectively). Unstandardised memory load effect sizes were 0.6% for ML(-) → ML(=) and 0.1% for the ML(=)→ML(+) (95% CIs [-1.0%, 2.4%] and [-1.7%, 1.6%]).

**Memory Load.** Dual-task verbal processing accuracy was analysed using the same procedure as previous experiments: the regression model is summarised in Table 5.11. The model contains significant effects of processing load, with participants being $\frac{1}{e^{-0.42}} = 1.52$ times more likely to produce a processing task error in the PL(=) condition compared to the PL(-) condition, and $\frac{1}{e^{-0.57}} = 1.77$ times more likely in the PL(+) condition. No statistically significant effects of memory load on processing accuracy were observed.

**Reaction Time Analysis.** Figure 5.9 displays mean RTs for (a) first items and (b) subsequent items. Linear models are summarised in Table 5.12. As with Experiments 6 and 7, there was only a significant effect of memory load for first item RTs. Neither model featured statistically significant interactions.
5.3. Experiment 8: + Articulatory suppression

Table 5.11: Experiment 8 - Summary of Logistic Regressions on Processing Accuracy

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficient (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.55 (0.09)***</td>
</tr>
<tr>
<td>[1] PL (-) to (=)</td>
<td>-0.42 (0.06)***</td>
</tr>
<tr>
<td>[2] PL (=) to (+)</td>
<td>-0.57 (0.05)***</td>
</tr>
<tr>
<td>[3] ML (-) to (=)</td>
<td>-0.04 (0.05)</td>
</tr>
<tr>
<td>[4] ML (=) to (+)</td>
<td>0.02 (0.05)</td>
</tr>
<tr>
<td>1:3</td>
<td>-0.20 (0.15)</td>
</tr>
<tr>
<td>1:4</td>
<td>0.12 (0.12)</td>
</tr>
<tr>
<td>2:3</td>
<td>0.10 (0.15)</td>
</tr>
<tr>
<td>2:4</td>
<td>-0.15 (0.12)</td>
</tr>
</tbody>
</table>

Num. obs. 2430
Num. groups: Participant 27

***p < 0.001, **p < 0.01, *p < 0.05

Figure 5.8: Experiment 8 - Mean processing accuracy (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities calculated from the coefficient estimates in Table 5.11 are plotted over mean accuracy data.
Table 5.12: Experiment 8 - Summary of Reaction Time Linear Regression Models

<table>
<thead>
<tr>
<th></th>
<th>First RTs</th>
<th>Subsequent RTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>643.52 (18.06)**</td>
<td>549.01 (17.55)**</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>15.44 (5.47)**</td>
<td>2.58 (4.17)</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>15.17 (5.50)**</td>
<td>−5.33 (4.17)</td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>−43.02 (5.59)**</td>
<td>−58.89 (4.17)**</td>
</tr>
<tr>
<td>1:3</td>
<td>−8.97 (13.20)</td>
<td>−11.52 (10.21)</td>
</tr>
<tr>
<td>1:4</td>
<td>−20.18 (13.18)</td>
<td>−15.40 (10.21)</td>
</tr>
<tr>
<td>2:3</td>
<td>1.55 (13.59)</td>
<td>−9.19 (10.21)</td>
</tr>
<tr>
<td>2:4</td>
<td>−3.61 (13.68)</td>
<td>11.34 (10.21)</td>
</tr>
<tr>
<td>Num. obs.</td>
<td>2237</td>
<td>2430</td>
</tr>
<tr>
<td>Num. groups</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

***p < 0.001, **p < 0.01, *p < 0.05
5.3. Experiment 8: + Articulatory suppression

Figure 5.9: Experiment 8 - Mean verbal processing reaction times for the first items (a) and subsequent items (b) (with bootstrapped confidence intervals) across each combination of memory load (ML) and processing load (PL). Predicted probabilities calculated from the coefficient estimates in Table 5.12 are plotted over mean accuracy data.
Discussion

The introduction of AS resulted in a clear effect of processing load on memory accuracy in the ‘at span’ memory load condition (ML[=]) (although processing task errors remain the best predictor of memory performance). Processing load affected memory performance differently in the ML(-) (‘below span’) and ML(+) (‘above span’) conditions (see Figure 5.7, page 146): accuracy was not affected between the PL(-) and PL(=) conditions for below span memory load, or between PL(=) and PL(+) for above span memory load. A clear effect of RPS was also observed, which was larger than those detected in Experiments 6 and 8.

Comparing the pattern of dual-task memory performance shown in Figure 5.7 with the results from previous experiments, the data for ‘below span’ memory accuracy under AS mirrors memory accuracy in the ML(=) and ML(+) conditions from Experiment 6 (no suppression). Although there was no significant interaction for the PL(-)→PL(=) increase in processing load in Experiment 6, the ‘at span’ memory performance in Experiment 7 closely resembles data from the ‘above span’ condition in the previous experiment (see Figure 5.1, page 117). Above span accuracy under AS resembles the overall pattern of memory performance observed in Experiment 6 (although the PL[-]→PL[=] effect was smaller in Experiment 6, and disappeared once errors were taken into account: see Figure 5.4 and Table 5.5, page 134).

Interpreting these effects in terms of a flexible working memory system with additional mechanisms for verbal rehearsal beyond simple subvocal rehearsal or use of phonological codes, it is clear that the introduction of AS resulted in a clear effect of concurrent processing task load on memory performance. We hypothesised that participants would rely on attention-based rehearsal when access to the phonological loop is prevented, and so predicted an effect of processing load across all memory load conditions. However, since accuracy in the ML(-) condition was unaffected by the processing load increase between PL(-) and PL(=) conditions participants...
may be relying on some other storage mechanism independent from attention or phonological rehearsal, or relying on these processes to a lesser degree. The average memory span in Experiment 7 was \( \sim 5 \) items, which would translate to a ‘residual’ capacity of around four items (i.e. \( \sim 80\% \) accuracy on 5-item lists). The absence of a processing load effect between PL(=) and PL(+) conditions in the ‘above span’ memory load condition can then be interpreted as another drop this residual capacity: given an average span of \( \sim 5 \), this would translate to residual memory capacity of \( \sim 2-3 \) items. The drops in accuracy in the ML(-) and ML(+) are likely due to the increased number of errors in the processing task, but even this effect appears to approach a residual level of performance in the latter condition.

Verbal processing accuracy was unaffected by concurrent memory load. In Experiment 6, the effect of memory load on processing accuracy was argued as evidence for the recruitment of attention-based resources to support sub-vocal rehearsal. The procedure in Experiment 6 may have predisposed participants towards phonological rehearsal methods in the single-task condition and so allowed detection of a ‘reallocation’ of processing resources in the dual-task condition (detected by the significant effect on processing accuracy). Nevertheless, memory rehearsal is assumed to be supported by attention-based processes in the dual-task condition. The absence of memory load effect on processing accuracy in Experiment 7 is likely due to the fact that participants are already using supplementary attention-based processes to support memory in the single-task condition. The addition of a concurrent task affects memory performance since it introduces a competition for resources, but the ‘reallocation’ of these resources is in the opposite direction from Experiment 6 - i.e. taking resources away from supplementing memory capacity in order to attend to the lexical decision task. This can explain why an effect of processing load on memory accuracy is observed in Experiment 6 and not Experiment 7, and why a clear effect of memory
load on processing accuracy is observed in Experiment 7 but not Experiment 6.
5.4 Between-experiment comparisons

The manipulations for Experiments 7 and 8 were based on the results of preceding experiments, with no plan for between-experiment analyses. However, a number of our conclusions are based on the different patterns of data observed in each experiment. For this reason additional analyses were completed to confirm that the different patterns of significant effects were statistically significant between experiments.

Single-Task Memory and Processing Spans

Single-task memory spans were significantly different between experiments \((F[2, 78] = 11.37, \eta^2_p = 0.23, p < 0.001)\). Pairwise comparisons confirmed that Experiment 8 span < Experiment 7 < Experiment 6 (all \(p < .05\)). Processing span did not differ between experiments \((F[2, 78] = 1.097, \eta^2_p = 0.03, p = 0.34)\).

Dual-Task Performance

In order to compare memory and processing performance across all three experiments and to compare the effects of shortening the presentation time of memory items (Experiment 7) or introducing AS (Experiment 8), we ran a logistic regression analyses which introduced a between subjects factor of ‘Experiment’. Experiment contrasts were dummy coded, with performance in Experiments 7 and 8 compared to performance in Experiment 6. Memory and processing performance were analysed separately.

Memory

Processing Load. The results from the analysis of processing load effects on memory accuracy can be seen in Table 5.13. The significant coefficients for each
### Table 5.13: Summary of Between-Subject (Experiment) Processing Load Logistic Regression on Memory Accuracy

<table>
<thead>
<tr>
<th>Model</th>
<th>(Intercept)</th>
<th>1.03 (0.11)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ML (-) to (=)</td>
<td>-0.60 (0.05)**</td>
</tr>
<tr>
<td>2</td>
<td>ML (=) to (+)</td>
<td>-0.46 (0.04)**</td>
</tr>
<tr>
<td>3</td>
<td>PL (-) to (=)</td>
<td>-0.00 (0.05)</td>
</tr>
<tr>
<td>4</td>
<td>PL (=) to (+)</td>
<td>-0.11 (0.05)*</td>
</tr>
<tr>
<td>5</td>
<td>Experiment 7 vs. 6</td>
<td>0.38 (0.16)*</td>
</tr>
<tr>
<td>6</td>
<td>Experiment 8 vs. 6</td>
<td>-0.51 (0.16)**</td>
</tr>
<tr>
<td>ProcErrors</td>
<td>-0.09 (0.01)**</td>
<td></td>
</tr>
<tr>
<td>1:3</td>
<td>0.22 (0.13)</td>
<td></td>
</tr>
<tr>
<td>2:3</td>
<td>-0.29 (0.11)**</td>
<td></td>
</tr>
<tr>
<td>1:4</td>
<td>-0.18 (0.13)</td>
<td></td>
</tr>
<tr>
<td>2:4</td>
<td>0.10 (0.10)</td>
<td></td>
</tr>
<tr>
<td>1:5</td>
<td>0.05 (0.08)</td>
<td></td>
</tr>
<tr>
<td>2:5</td>
<td>-0.10 (0.06)</td>
<td></td>
</tr>
<tr>
<td>1:6</td>
<td>0.21 (0.07)**</td>
<td></td>
</tr>
<tr>
<td>2:6</td>
<td>0.00 (0.06)</td>
<td></td>
</tr>
<tr>
<td>3:5</td>
<td>-0.06 (0.07)</td>
<td></td>
</tr>
<tr>
<td>4:5</td>
<td>0.18 (0.07)*</td>
<td></td>
</tr>
<tr>
<td>3:6</td>
<td>-0.10 (0.07)</td>
<td></td>
</tr>
<tr>
<td>4:6</td>
<td>-0.02 (0.07)</td>
<td></td>
</tr>
<tr>
<td>1:3:5</td>
<td>-0.28 (0.20)</td>
<td></td>
</tr>
<tr>
<td>2:3:5</td>
<td>0.17 (0.16)</td>
<td></td>
</tr>
<tr>
<td>1:4:5</td>
<td>0.34 (0.19)</td>
<td></td>
</tr>
<tr>
<td>2:4:5</td>
<td>-0.08 (0.16)</td>
<td></td>
</tr>
<tr>
<td>1:3:6</td>
<td>-0.54 (0.18)**</td>
<td></td>
</tr>
<tr>
<td>2:3:6</td>
<td>0.25 (0.15)</td>
<td></td>
</tr>
<tr>
<td>1:4:6</td>
<td>0.31 (0.18)</td>
<td></td>
</tr>
<tr>
<td>2:4:6</td>
<td>0.15 (0.15)</td>
<td></td>
</tr>
</tbody>
</table>

| Num. obs. | 7290 |
| Num. groups: Participant | 81 |

***p < 0.001, **p < 0.01, *p < 0.05
5.4. Between-experiment comparisons

experiment (labelled ‘5’ and ‘6’ in the table) mean that dual-task memory accuracy was better when the presentation time for memory items was shortened (Experiment 7), and worse under AS (Experiment 8).

The significant interaction labelled ‘2:3’ means that, across all three experiments, participants memory accuracy was affected to a greater degree between ML(=) and ML(+) memory load (ML) conditions for the PL(-)→PL(=) load increase. The interaction labelled ‘1:6’ means the drop in memory performance between ML(−) and ML(=) conditions was smaller in Experiment 8 compared to Experiment 6. The ‘4:5’ interaction means the PL(−)→PL(+) increase in load was less disruptive to memory performance in Experiment 7 compared to Experiment 6.

The three-way interaction labelled ‘1:3:6’ confirms that the effect of increasing memory and processing load from ‘below span’ to ‘at span’ has a larger effect on memory performance in Experiment 8 compared to Experiment 6.

Retrievals-per-second (RPS). A number of the results shown in Table 5.14 duplicate results from the analysis of processing load, and so are not reiterated here.

The RPS regression analysis revealed no overall effect of RPS on memory accuracy across the three experiments (p = 0.10). However, the interaction labelled ‘2:3’ means that, across all three experiments, the effect of RPS was larger between the ML(=) and ML(+) conditions. Also, the interaction labelled ‘3:5’ in Table 5.14 reveals that the effect of RPS was larger in Experiment 8 compared to Experiment 6, whilst the ‘2:3:5’ interaction confirms that this effect was smaller in Experiment 8 than in Experiment 6.
Table 5.14: Summary of Between Subjects (Experiment) RPS Logistic Regression on Memory Accuracy

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficient</th>
<th>Standard Error</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.03 (0.11)***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>-0.60 (0.05)***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>-0.46 (0.04)***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[3] RPS</td>
<td>-0.19 (0.12)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[4] Experiment 7 vs. 6</td>
<td>0.38 (0.16)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[5] Experiment 8 vs. 6</td>
<td>-0.51 (0.16)**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ProcErrors</td>
<td>-0.10 (0.01)***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:3</td>
<td>0.05 (0.20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2:3</td>
<td>-0.43 (0.16)**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:4</td>
<td>0.05 (0.08)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2:4</td>
<td>-0.11 (0.06)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:5</td>
<td>0.21 (0.07)**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2:5</td>
<td>-0.01 (0.06)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3:4</td>
<td>0.28 (0.17)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3:5</td>
<td>-0.38 (0.16)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:3:4</td>
<td>-0.15 (0.27)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2:3:4</td>
<td>0.32 (0.22)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:3:5</td>
<td>-0.29 (0.27)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2:3:5</td>
<td>0.89 (0.23)***</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Num. obs. 7290
Num. groups: Participant 81
Num. groups: Experiment 3

* * * p < 0.001, ** p < 0.01, * p < 0.05
5.4. Between-experiment comparisons

Processing

**Accuracy.** The results from the between-experiment analysis of processing accuracy are shown in Table 5.15. The analysis revealed that, across the three experiments, only the ML(−)→ML(=) increase in load resulted in a statistically significant drop in processing accuracy. No differences in performance between experiments were found, and no significant interactions.

**Reaction Time.** The between-experiment analyses of processing task reaction time (RT) are shown in Table 5.16. The analysis of first-item RTs revealed significant effects of increasing memory load from ‘below span’ to ‘at span’ to ‘above span’ across all three experiments. No significant effects of memory load on subsequent-item RTs were found. RTs for first and subsequent items were slower in Experiment 8 than in Experiment 6, but no interactions were detected.
### Table 5.15: Summary of Between Subjects (Experiment) Memory Load Logistic Regression on Processing Accuracy

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficient</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>1.46 (0.10)**</td>
<td></td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>-0.11 (0.05)*</td>
<td></td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>-0.10 (0.05)</td>
<td></td>
</tr>
<tr>
<td>[3] PL (-) to (=)</td>
<td>-0.45 (0.05)**</td>
<td></td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>-0.48 (0.04)**</td>
<td></td>
</tr>
<tr>
<td>[5] Experiment 7 vs. 6</td>
<td>-0.13 (0.14)</td>
<td></td>
</tr>
<tr>
<td>[6] Experiment 8 vs. 6</td>
<td>0.09 (0.14)</td>
<td></td>
</tr>
<tr>
<td>1:3</td>
<td>0.12 (0.14)</td>
<td></td>
</tr>
<tr>
<td>2:3</td>
<td>0.12 (0.13)</td>
<td></td>
</tr>
<tr>
<td>1:4</td>
<td>-0.09 (0.11)</td>
<td></td>
</tr>
<tr>
<td>2:4</td>
<td>-0.00 (0.11)</td>
<td></td>
</tr>
<tr>
<td>1:5</td>
<td>-0.05 (0.07)</td>
<td></td>
</tr>
<tr>
<td>2:5</td>
<td>-0.07 (0.07)</td>
<td></td>
</tr>
<tr>
<td>1:6</td>
<td>0.07 (0.07)</td>
<td></td>
</tr>
<tr>
<td>2:6</td>
<td>0.11 (0.07)</td>
<td></td>
</tr>
<tr>
<td>3:5</td>
<td>-0.09 (0.08)</td>
<td></td>
</tr>
<tr>
<td>4:5</td>
<td>-0.03 (0.06)</td>
<td></td>
</tr>
<tr>
<td>3:6</td>
<td>0.03 (0.08)</td>
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</tr>
<tr>
<td>4:6</td>
<td>-0.09 (0.07)</td>
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</tr>
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**Num. obs.** 7290  
**Num. groups: Participant** 81  

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$***
Table 5.16: Summary of Between Subjects (Experiment) Logistic Regressions on RT

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<th></th>
<th>First RTs</th>
<th>Subsequent RTs</th>
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<tr>
<td>(Intercept)</td>
<td>619.10 (8.03)***</td>
<td>512.36 (6.27)***</td>
</tr>
<tr>
<td>[1] ML (-) to (=)</td>
<td>13.41 (6.35)*</td>
<td>-2.46 (5.03)</td>
</tr>
<tr>
<td>[2] ML (=) to (+)</td>
<td>20.76 (6.39)**</td>
<td>-5.07 (5.03)</td>
</tr>
<tr>
<td>[3] PL (-) to (=)</td>
<td>-22.38 (6.29)***</td>
<td>-31.44 (5.03)***</td>
</tr>
<tr>
<td>[4] PL (=) to (+)</td>
<td>-43.56 (6.47)***</td>
<td>-51.66 (5.03)***</td>
</tr>
<tr>
<td>[5] Experiment 7 vs. 6</td>
<td>-0.07 (3.70)</td>
<td>1.94 (2.90)</td>
</tr>
<tr>
<td>[6] Experiment 8 vs. 6</td>
<td>25.93 (3.67)***</td>
<td>36.65 (2.90)***</td>
</tr>
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<td>2:3</td>
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</tr>
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</table>

Num. obs. 6605 7290
Num. groups 27 27

***p < 0.001, **p < 0.01, *p < 0.05
5.5 Summary and interpretation of Experiments 6-8

Experiment 6 investigated the effect of varying both memory and processing load according to participants’ individually measured spans on each task, while Experiments 7 and 8 introduced small manipulations to the experimental procedure aimed at encouraging the use of specific rehearsal methods.

Experiment 6 (longer encoding time, no AS) revealed a statistically significant effect of processing load on memory accuracy, but only when list lengths exceeded their single-task memory capacity. Crucially, the processing task did not affect memory performance when list length was set below participants' span (in Experiment 6, this was an average list length of \(\sim 5\) items). Memory load had a small effect on processing accuracy in Experiment 6, with the only statistically significant effect being the increase from ‘below span’ list lengths to ‘at span’ list lengths (although the coefficient for the ‘at span’ to ‘above span’ increase was near significant).

Our interpretation of these data assumes that humans possess a specialised yet capacity-limited verbal store, with rehearsal relying on sub-vocal articulation of to-be-remembered items. By testing participants to their verbal memory capacity in the single-task conditions we encourage the use of additional attention-based rehearsal mechanisms to allow the retention of lists beyond the base capacity facilitated by the phonological store and sub-vocal rehearsal. The introduction of a secondary task allows us to detect a point at which participants begin to rely more heavily on attention-based rehearsal methods: concurrent processing load having no effect on memory accuracy when lists are set below participants’ span, and having a much larger effect when processing load is set above participants’ single-task capacity. The small effect of memory load on processing accuracy and reaction times betrays this
switch of attention to support increasing list lengths.

The presentation time for memory items was halved for Experiment 7 to encourage the use of more automated processes for rehearsal, namely the use of phonological codes and sub-vocal rehearsal. This manipulation reduced (and partly reversed) the effect of processing load on memory accuracy, suggesting a separation of verbal memory and verbal processing during the maintenance period of the task. While single-task memory spans were lower in Experiment 7 compared to Experiment 6, the cost of introducing the concurrent task to the maintenance interval was less severe as dual-task performance was better when participants were prevented from recruiting additional resources due to the speeded nature of the memory task.

Our interpretation of the different patterns of verbal processing performance between Experiments 6 and 7 is that when participants were allowed sufficient time to study the memory items they recruited additional rehearsal and maintenance strategies above and beyond simple phonological rehearsal or attention-free storage such as that provided by the phonological loop. When memory items were only presented briefly, as they were in Experiment 7, a purer measure of participants’ verbal memory stores was obtained. The different patterns of dual-task processing performance between these two conditions occur as a result of the differences in scope for supporting memory performance. In Experiment 6, participants were already utilising attention-based resources to their full extent in the single-task condition. Participants in Experiment 7 would not yet have recruited additional resources to support memory performance in the single-task condition (resulting in lower spans), but when task difficulty is increased with the introduction of a secondary task this recruitment is evident in the drop in performance of the concurrent processing task.

Conversely, encouraging the use of attention-based rehearsal negatively affected dual-task performance. Experiment 8 introduced AS to the procedure of Experiment
6. This again resulted in lower single-task memory spans, but dual-task memory performance was also poorer than that observed in Experiment 6 (in contrast with the improvement seen in Experiment 7). We interpret this as evidence for the recruitment of rehearsal methods that require attention. Attention-based rehearsal/maintenance methods appear to be less effective than phonological codes (evident in the difference between single-task memory spans Experiments 7 and 8), and reduce participants ability to coordinate concurrent memory and processing tasks by creating an attentional demand for each task. Since participants were unable to sub-vocally rehearse due to AS they would have to rely purely on attention-based maintenance methods in the dual-task condition. The lack of memory load effect on processing accuracy in the dual-task condition may arise because there is no further scope for attention to support verbal memory performance, and so no trade-off is observed.

Our experimental procedure meant that each participant was tested on three consecutive list lengths based on their single-task span (smaller increases in demand compared to those usually utilised in the TBRS literature). Our analyses of RPS allowed examination of performance across all ‘cognitive load’ values as investigated by Barrouillet et al. (2004) and Barrouillet et al. (2007), but with the benefit that participants are completing tasks set at appropriate levels of difficulty for their own abilities (especially for high RPS conditions). For Experiment 6, the analysis revealed that the RPS (or ‘cognitive load’) effect was limited to when participants were presented with lists set above their own memory capacity. RPS was a poor predictor of memory performance in Experiment 7, while a strong effect of RPS was found in Experiment 8. These results, along with the analyses of the effects of processing load, support our hypothesis that the experimental manipulations between Experiments 6, 7, and 8 affected how participants approached the memory task by limiting or encouraging either sub-vocal rehearsal or attention-based refreshing.
It is important to note that for all three experiments the effects of processing load and RPS were far smaller than the effects of increasing memory load by one item. The effect of making a single error in the processing task also produced far larger effects on memory accuracy than increases in processing load or RPS. It is therefore difficult to separate the relatively small effects of processing load from the inevitably higher error rates in high-demand conditions.

The fact that memory load has such small effects on processing accuracy suggests that participants’ ability to maintain ‘at span’ and ‘above span’ list lengths requires access to an attention-based resource above and beyond what is provided by default maintenance methods. Processing load effects on memory performance are consistently observed while memory load effects on processing are not, suggesting that performance on the processing task is not supported by memory-specific resources, but that some processing resource can be used to support memory performance.
Chapter 6

Experiment 9: Task Priority
6.1 Introduction

As discussed in Chapter 1, the TBRS methodology puts particular emphasis on processing performance to ensure that sufficient attention is paid to the presented tasks in order to facilitate a switch of resources away from maintenance of memory items. To ensure this the TBRS literature often features strict accuracy criteria for the processing tasks, and participants are often removed for not meeting these criteria (e.g Camos et al., 2009; Vergauwe et al., 2009, 2014).

While our single-task processing spans were measured using a pass criteria of 80% accuracy, our dual-task procedures involved testing participants on processing tasks set above their calculated spans. Due to this, dual-task processing accuracy dropped below this 80% accuracy in the above-span load conditions in all of our experiments. It could therefore be argued that if the processing tasks become too difficult for participants they may not pay close enough attention to the task to result in a sufficient diversion of attention as said to be required by the TBRS model.

However, the fact that in all of the experiments reported here\(^1\) the only effects of processing load were observed when the processing tasks were set above span suggests that this is not the case. These above-span affects could be due to error processing, but in our analyses the inclusion of the processing errors factor did not negate the processing load effects: both appear to have an additive effect on memory performance.

Despite this, anonymous reviewers of Doherty and Logie (2016) raised concerns about the perceived priority of the memory and processing tasks, and linked this to the possibility that participants were paying insufficient attention to the processing tasks to elicit the ‘cognitive load’ effect described by the TBRS model. We therefore deemed it important to test whether participants are able to prioritise either

\(^1\)Aside from Experiment 8, which included AS to encourage the use of attentional resources for memory.
the memory or processing task, and to observe how different task priorities affect performance. The instructions given to participants in Experiments 1-8 contained no information regarding the priority of the two tasks, beyond instructing participants to complete both tasks to the best of their abilities. Experiment 9 aimed to investigate the effect of instructed priority on memory and processing performance.

In Chapter 3 we discussed Morey et al.’s (2013) analysis of a trade-off between visual and verbal memory. The procedure followed by Morey et al. (2013) was based on a previous study by Morey et al. (2011), which found evidence for a trade-off between a visual memory task and an auditory memory task. Participants were presented with visual arrays and tone sequences. Each task required a detection of a ‘change’ between two presentations separated by a maintenance interval. The visual arrays contained coloured squares, and a change would mean one square was a different colour in the second presentation. For the auditory memory task, two sequences of tones were separated by a maintenance interval, and would either be the same or would differ in one tone in the sequence. Presentation and test phases of each task were presented in an alternating sequence, meaning that a participant would see a visual array, followed by a sequence of tones, followed by a test array, followed by a test sequence of tones (or in the reverse order). Morey et al. (2011) varied the reward for each task, allocating gradated priority to each task, with a different number of ‘points’ being awarded for each task. These points were then converted into financial rewards at the end of the experiment. The authors reported trade-off effects between the two tasks, suggesting a flexible allocation of a domain-general resource.

Morey et al. (2011) chose an auditory, non-verbal memory task over an auditory verbal task based on the assumption that tones cannot be rehearsed in the same way as letters of words (but see Logie & Edworthy, 1986; Schendel & Palmer, 2007;
Williamson, Mitchell, Hitch, & Baddeley, 2010), and so the auditory task should rely more heavily on a central resource than a verbal task. However, Morey et al.’s (2013) investigation of trade-off did utilise a visually presented verbal task, and found that unlike visual memory verbal memory did not suffer a gradated trade-off effect: memory accuracy remained at single-task levels unless participants were instructed to wholly prioritise the visual memory task. Because our procedures involved a visually presented verbal memory task, and because we are interested in whether a trade-off between processing and memory tasks is possible, we compared performance in conditions where one or the other task was given full priority, compared to control conditions where both tasks had equal priority.

Experiment 9 also aimed to test whether participants’ memory and processing performance was stable across the course of the experimental session. Our interpretations rely heavily on not only our span measures providing an accurate estimate of participants’ memory capacity and ability on the processing task, but also that their performance on each is not affected by fatigue or practice over the time frame of a typical experiment. Experiment 9 therefore included two single-task memory blocks for each task in addition to the span procedures. Single-task memory and processing blocks were completed after the span procedures but before the dual-task conditions, and repeated at the end of the session.
6.2 Method

Participants and Apparatus.

Twenty-four participants took part in the experiment in exchange for an honorarium. The sample consisted of 8 males and 16 females, mean age = 22.6 (range = 18-33). The experiment was conducted using the same equipment detailed in Chapter 5.

Procedure.

Experiment 9 used the same verbal memory memory and verbal processing tasks described in Experiment 6.

Single-Task Conditions.

Single-task memory and processing spans were first measured using the 4/5 span procedure, as in previous experiments. Participants were then given ten single-task trials set at ‘span +1’ before and after the dual-task conditions. This was to allow direct comparison between single- and dual-task conditions, as well as providing a check that participants were not demonstrating practice or fatigue effects over the course of the experiment. Task loads were set at ‘span +1’ to avoid ceiling affects in the single-task conditions, and to encourage the use of multiple modes of rehearsal or maintenance. Another modification to the procedure was that participants were instructed to guess memory items if they could not remember, or enter a question mark (‘?’) if they were unsure of what to enter. In previous experiments participants were required to provide letters for every position in the list.
Dual-Task Conditions.

Participants completed four dual-task conditions with different pre-trial instructions and post-trial feedback. These conditions were named ‘No Instruction’ (NI), ‘Memory Priority’ (MP), ‘Processing Priority’ (PP), and ‘Equal Priority’ (EP). Each condition consisted of ten trials with the memory and processing tasks set at ‘span +1’.

**No Instruction (NI).** In this condition, participants completed both tasks with no task labelled/implied as being more important. The NI condition always preceded the other conditions, but subsequent conditions were counterbalanced between participants.

**Priority Conditions.** In the priority dual-task conditions participants were given an instruction before each trial indicating which task had priority, e.g. “Memory task (letters) is the priority task” (N.B. these were blocks of trials with the same task priority: the instruction before each trial simply served as a reminder). After each trial participants were provided feedback for the priority task, e.g. “Memory Accuracy: 74%”. Participants were instructed to complete both tasks to the best of their ability, but to focus on the priority task in order to achieve a higher ‘score’.

In the ‘Equal Priority’ condition, participants were instructed that “Both tasks have equal priority”, and were provided feedback in the form of an average performance across both tasks: e.g. “Dual-task performance: 74%”.

6.3 Results

Single-task memory and processing spans were 6.1 ($SD = 0.9$) and 6.6 ($SD = 1.2$) respectively. Note that for both memory and processing tasks, single-task performance was stable across the length of the experiment (i.e. no difference in accuracy between the first and second single-task conditions, administered before and after the dual-task conditions: $BF$ for memory span = $5.2 \pm 0.19\%$ against a difference, for processing span $BF = 4.49 \pm 0.14\%$).

Memory and processing performance were analysed separately via hierarchical logistic regression. The same method of backwards difference coding (X. Chen et al., 2003) that was used in previous experiments compared performance in each condition with the preceding condition. Memory and processing accuracy are shown in Figure 6.1, and the analyses of memory and processing performance are summarised in Table 6.1.

The analysis of memory accuracy revealed a significant drop in performance between single-task and the first dual-task conditions (‘No Instruction’, NI): participants were $\frac{1}{e^{-1.35}} = 3.86$ times more likely to produce a memory task error in the NI condition compared to the single-task (ST2) condition. Memory performance was slightly improved when the memory task had priority (PM) ($e^{0.18} = 1.20$ times more likely to respond correctly), however performance in the MP condition was not significantly improved compared to the EP condition. Memory performance is greatly affected by the switch of priority to the processing task (PP), with memory task errors being $\frac{1}{e^{-0.61}} = 1.84$ more probable in the PP condition compared to the EP condition.

Processing accuracy was also negatively affected by the introduction of dual-tasking, with a $\frac{1}{e^{-0.53}} = 1.70$ increase in the likelihood of making a processing task error in the NI condition compared to the single-task condition (ST2). Contrary
Figure 6.1: Experiment 9 - Mean memory and processing accuracy (with bootstrapped confidence intervals) across all single- and dual-task conditions.

to the results from the memory analysis, processing accuracy was not affected by the switch of task priority (see MP vs. NI in the processing section of Table 6.1). Performance was improved between the PM and EP conditions (participants were $e^{0.4} = 1.49$ times more likely to produce a correct response), but as with the memory analysis processing accuracy in the EP condition was no different than when the processing task has priority. A post-hoc analysis of processing accuracy between the ST1, ST2, EP and PP conditions revealed strong evidence against any differences in performance ($BF = 10.0 \pm .56\%$ against an effect).
6.3. Results

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<th>Coefficient</th>
<th>Standard Error</th>
<th>Significance</th>
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<td></td>
<td>***</td>
</tr>
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<td></td>
</tr>
<tr>
<td>No Instruction (NI) vs. ST2</td>
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<td>***</td>
</tr>
<tr>
<td>Memory Priority (MP) vs. NI</td>
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<td>*</td>
</tr>
<tr>
<td>Equal Priority (EP) vs. MP</td>
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<td></td>
</tr>
<tr>
<td>Processing Priority (PP) vs EP</td>
<td>-0.61 (0.07)</td>
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Num. obs. 1440
Num. groups: Participant 24

Table 6.1: Experiment 9 - Summary of Logistic Regressions on Memory and Processing Accuracy.
6.4 Discussion

Experiment 9 tested whether participants could selectively prioritise either the memory or processing task during dual-tasking, while also serving as a check that single-task memory and processing performance was stable across the course of an experiment session. This second point was confirmed as for both memory and processing, as single-task performance from the start and end of the sessions did not differ from one another.

Participants’ memory accuracy was marginally higher when the memory task was given priority (‘Memory Priority’, MP) compared to when participants were given no priority instructions (‘No Instruction’, NI). Importantly, performance in the ‘Equal Priority’ (EP) condition was not lower than in the MP condition. Because the NI condition always preceded the priority conditions the difference in performance between this condition and the MP condition is likely to be due to some small dual-task practice effect. The lack of effect between the counterbalanced MP and EP conditions suggests that participants are unable to prioritise the memory task when instructed, yet the ‘cost’ to processing accuracy was observed between these two priority conditions. Likewise, memory accuracy was severely affected by instructing participants to focus on the processing task in the ‘Processing Priority’ (PP) condition. However, this cost to memory accuracy was not met with an improvement in processing performance, as accuracy on the latter task did not differ between the EP and PP conditions.

The finding that priority instructions only affected the non-priority task, with no improvement in participants’ performance in the priority task, is reassuring when considered in the context of the other experiments in this thesis. As mentioned previously, participants in our previous experiments were instructed to complete both tasks to the best of their ability. In Experiment 9, no difference in performance
on either task was found between the condition in which it was given priority and the condition in which participants were instructed to focus on both tasks. This suggests that in order to observe the ‘best’ dual-task performance participants should be instructed to complete both tasks to the best of their ability. The drops in non-priority task performance are likely to be due to some intentional effort to neglect the task in order to ‘boost’ performance in the priority task, even if no such boost to performance is achieved.

It is notable that participants’ performance in the PP and EP conditions was at single-task levels. This supports the hypothesis that single-task memory performance is ‘boosted’ by resources related to the processing task, and that during dual-task conditions memory performance drops to a level representative of a pure verbal memory capacity. Focussing on the PM and EP conditions, it is clear that memory performance remains stable even when processing accuracy is at a single-task level of performance. These data strongly support an ability to dual-task memory and processing with small costs to memory performance when task loads are set according to participants’ spans.

The effect of allocating priority to the processing task on memory accuracy was striking, with a drop in performance of approximately 10%. This may suggest that even implied priority could have large effects on memory accuracy. We have discussed in previous sections that the TBRS model places particular importance on performance on the processing task in order to ensure that sufficient attention is paid to processing in order to allow memory decay, with participants and trials being excluded from analyses in order to fulfil processing task performance criteria. It is therefore possible that participants in the TBRS studies may have perceived the processing task as being of greater priority than the memory task, either due to the fact that they are given extensive practice on the task or due to the experimenters
monitoring of their performance (errors on a choice-RT task are more immediately apparent to both the subject, and to an onlooker, than errors in typed recall). This could also explain the effects of processing errors observed in Experiments 3-8, as participants may attempt to prioritise the processing task as they make more errors in the high processing load conditions by sacrificing performance on the memory task.

Another interpretation of these effects could be that different stages of encoding and maintenance require different levels of attention, and that it is only when attention is fully diverted from memory that an effect is observed. The lack of priority effect between the EP and MP conditions are in line with Morey et al.’s (2013) study in which memory for visually presented numbers was only affected when the concurrent visual memory task was given 100% priority. Naveh-Benjamin and Jonides (1984) proposed a two-stage process of maintenance and rehearsal in which the first stage involves activating an articulatory rehearsal program, while the second stage consists of the actual subvocal rehearsal process. The authors state that while the first stage of the process is cognitively demanding, the second stage is relatively automated. This order of operations, and the difference in cognitive demand between the two stages, could explain the large effects on first-item RTs observed in Experiments 6-8, and in Vergauwe et al. (2014). This two-stage process could also explain why verbal memory is not affected by gradated shifts in task priority, as it is only once the secondary task is given full priority that the first stage of Naveh-Benjamin and Jonides’s (1984) process is affected.

To summarise, Experiment 9 confirms that single-task memory and processing performance is the same at the end of the experiment compared with when it was measured prior to the dual-task conditions. This is an important finding since the interpretation of our ‘below span’→‘at span’→‘above span’ manipulations rested on
the assumption that memory and processing ability was constant. This experiment also confirms that the instructions given to our participants in our previous experiments likely resulted in the best dual-task performance across both tasks. We can not be 100% certain that participants approached tasks with equal priority, but we can be sure that instructions to focus on one task can affect performance on the other task. For this reason, in future studies, we will be sure to explicitly instruct participants to give each task equal priority as this was the instruction that resulted in optimal dual-task performance.
Chapter 7

General Discussion
7.1 Summary of main research findings.

The research presented here investigated the effect of memory and processing load on dual-task performance. Our initial investigation focussed on the effect of titrating task demand on participants’ individually measured memory and processing spans. Previous research has shown that titrating task demand results in very small dual-task costs (Cocchini et al., 2002; Logie et al., 2004), and Doherty and Logie (2016) found no effect of a titrated concurrent processing task on memory span. These findings provide further evidence for the importance of evaluating dual-task costs in terms of single-task performance, with sub-task demands adjusted to the capacities of each participant. The main findings from Chapters 2-6 are summarised in Table 7.1.

Doherty and Logie (2016) also found effects of above-span memory load on concurrent processing accuracy. This was interpreted as an effect of a general attention resource being utilised by participants to support memory performance for lists exceeding their capacity. Doherty and Logie’s analysis of processing accuracy relied on a comparison of performance in the last level of each dual-task memory span condition and the previous level. As a result it wasn’t possible to rule out that such a trade-off may occur for all list lengths and that the absence of a dual-task effect on memory span was due to participants placing greater priority on the memory task than in studies demonstrating a TBRS ‘cognitive load’ effect.

Experiment 1 remeasured processing ability under different memory loads. Again, the difficulty of the memory task was set according to single-task memory span for each participant. The results revealed that processing performance was affected by concurrent memory load only for lists set above participants’ single-task span (see Figure 2.4, page 53). The RT analysis revealed no effect of memory load. A small effect of processing load was found on memory accuracy, but the Bayes factor analysis
Table 7.1: Summary of findings from Chapters 2-6.

Key: VM=Verbal Memory, SP=Spatial Processing, VPT=Visual Patterns Task, VP=Verbal Processing

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<thead>
<tr>
<th>Chapt.</th>
<th>Experiment</th>
<th>Description</th>
<th>Main Finding(s)</th>
</tr>
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<td>VM &amp; SP</td>
<td>Mem: Unaffected by processing load (PL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proc: Affected by above-span memory load (ML)</td>
</tr>
<tr>
<td>1</td>
<td>SP &amp; VM</td>
<td></td>
<td>Mem: Weak evidence for effect of PL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proc: Affected by above-span ML</td>
</tr>
<tr>
<td>2</td>
<td>VPT &amp; SP</td>
<td></td>
<td>Mem: Above span (+2) effect of PL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proc: No effect of ML</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>VPT &amp; SP</td>
<td>Mem: Effect of ML and PL only ‘above span’</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proc: No effect of ML</td>
</tr>
<tr>
<td>4</td>
<td>VPT &amp; VP</td>
<td></td>
<td>Mem: No effect of PL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proc: No effect of ML</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>VM &amp; SP</td>
<td>Mem: Effect of above-span PL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proc: Effect of above-span ML</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>VM &amp; VP</td>
<td>Mem: Effect of above-span PL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proc: Full effect of PL for above-span ML</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proc: Effect of ML between below- &amp; at-span ML</td>
</tr>
<tr>
<td>7</td>
<td>VM &amp; VP</td>
<td>w/Short Pres.</td>
<td>Mem: Small/non-sig. effects of PL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proc: Effect of ML</td>
</tr>
<tr>
<td>8</td>
<td>VM &amp; VP</td>
<td>w/AS</td>
<td>Mem: Effect of PL for all ML conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Interaction suggesting ‘residual’ memory</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proc: No effect of ML</td>
</tr>
<tr>
<td>9</td>
<td>Priority</td>
<td></td>
<td>Best dual-task performance for ‘Equal Priority’</td>
</tr>
</tbody>
</table>

provided weak evidence against the effect (1.37 ± .45%) meaning the analysis was inconclusive.

A concern was that the ‘span –1’→‘span +2’ manipulation was not sufficient to elicit a processing load effect in Doherty and Logie (2016). Experiment 2 therefore introduced a visual patterns task in place of the digit span task utilised in previous experiments. We hypothesised that due to the overlap in representations of a visual and spatial task there would be a larger dual-task cost and greater interference between tasks. The results of the analyses revealed a significant effect of processing load only when it was set two levels above single-task span. Again, no effect of memory load on processing accuracy was observed.

Doherty and Logie’s (2016) analysis of verbal memory span and Experiment
7.1. Summary of main research findings.

1 suggested that memory performance can be supplemented by the same attentional resource responsible for the processing task, explaining the above-span effect on processing performance but not on memory. This effect wasn’t observed in Experiment 2, assumed in part to be due to the lack of sensitivity afforded by analysing blocked data. Experiments 3 and 4 developed the titrated-demand methodology of previous experiments to allow manipulation of both memory and processing load within the same procedure, while also facilitating a more sensitive measure of performance. Experiment 3 revealed an above-span effect of spatial processing load on visual memory but the effect of memory load on processing accuracy was not present in the dual-task conditions. Experiment 4 substituted a verbal processing task for the spatial task used in previous experiments, which resulted in clear memory load effects on memory accuracy but no effect of processing load on recall.

After concluding that the visual patterns task did not provide a pure delineation between memory loads, we switched back to verbal memory tasks for the remaining experiments. Considering that the mechanisms for verbal rehearsal have been extensively investigated, that research into the role of both attention and sub-vocal rehearsal mechanisms on verbal memory have been a focus of the TBRS model (Camos et al., 2009, 2011), and that processing/memory trade-offs have been observed using similar tasks (Experiment 1; Doherty & Logie, 2016; Vergauwe et al., 2014), the use of a verbal memory task was deemed most likely to allow detection of above-span involvement of attention in memory.

Experiment 5 therefore paired a verbal memory task with a spatial processing task, and found an above-span effect of processing load on memory accuracy. In contrast to the experiments which utilised a visual memory task, Experiment 5 also found an above-span effect of memory load on processing accuracy. Experiment 6 replicated these effects with a verbal processing task, except that processing load
affected above-span memory load for both increases in processing load, not just the PL(=)→PL(+). These effects supported the hypothesis that attention-based resources are recruited when memory load is set above span.

Following on from this, Experiments 7 and 8 each aimed to encourage the use of phonological-based rehearsal and attention-based refreshing respectively. Experiment 7 reduced the presentation time of memory items in an attempt to lessen participants’ opportunities to recruit additional resources above and beyond the phonological store and sub-vocal rehearsal. Experiment 8 required participants to repeat “ba ba ba...” throughout the presentation of memory stimuli and during the processing task interval. The results of these two manipulations were clear in both single-task spans and in dual-task performance. Both the shorter presentation time manipulation and the addition of AS lowered single-task spans, but affected dual-task performance differently. Despite poorer single-task performance, shorter presentation of memory items resulted in stable memory accuracy across all processing load levels. Conversely, the addition of AS resulted in poorer dual-task memory performance compared to the control experiment (Experiment 6), with processing load having an effect on memory accuracy at ‘below span’, ‘at span’, and ‘above-span’ list lengths. Processing performance also differed between Experiments 7 and 8, with processing being affected by memory load in the former experiment but not in the latter (though these differences were not found in the between-experiment analysis, see Table 5.13, page 157).

A potential confound in the procedure raised by reviewers was that participants may be giving higher priority to either the memory or processing task in some conditions. In order to assess this, Experiment 9 compared participants’ memory and processing accuracy under different priority instructions. The best dual-task performance was observed when participants were instructed to give both tasks equal
7.2 Interpretation within the context of MCM and TBRS frameworks

priority. Instructing them to prioritise one task over the other resulted in a severe
detriment to performance on the non-priority task, however this ‘cost’ was revealed
to be apparent rather than real as no improvement to the priority task was observed.
Two possible interpretation of the results were discussed: participants may be unable
to switch attention between tasks, and any effects were an artefact of participants’
explicit attempts to partially ‘ignore’ the non-priority task; verbal memory perfor-
mance requires little attention, or only requires attention at certain points in the
rehearsal sequence (Morey et al., 2013; Naveh-Benjamin & Jonides, 1984).

The results of the instructed priority experiment could also explain the effect of
the number of processing errors made by participants on memory accuracy. Exper-
iment 9 revealed that shifting priority to the processing task had a large effect on
memory accuracy with no apparent benefit to the former task. The processing error
effects observed in Experiments 3-8 were all relatively large compared to processing
load and RPS effects, so it may be that once participants start to make a larger
number of errors on the lexical decision or spatial judgement tasks they shift their
priority to these tasks.

7.2 Interpretation within the context of MCM

and TBRS frameworks

While the main findings are incompatible with the earlier multiple component and
TBRS models (e.g. Baddeley, 1986; Baddeley & Logie, 1999; Barrouillet et al.,
2004), they are congruent with recent work on each theory (e.g. Logie, 2011; Camos
et al., 2009, 2011).
MCM.

Overall, the small or non-significant dual-task effects (Experiment 9; Doherty & Logie, 2016) and general lack of secondary task demand in most memory load conditions in the presented experiments fit with the MCM’s assumption of separable memory and processing components (Baddeley, 1986; Duff & Logie, 1999, 2001). In particular, Doherty and Logie’s (2016) investigation of span, and Experiment 1, suggest a separation of processing and storage due to the lack of effect of processing load on memory. Compared to other studies showing no processing-storage interference for at-span tasks (Cocchini et al., 2002), all the non-AS verbal memory experiments strongly suggest that memory can operate in parallel with a processing task.

As discussed previously, Logie (2011) suggested that domain-general effects may be observed when otherwise separate working memory components’ capacities are exceeded. The above-span effects reported here, in particular those observed in memory performance, support Logie’s hypothesis. Within the context of the MCM, the additional support for verbal memory could come from increased use of visual strategies (e.g. Saito et al., 2008; Logie, Saito, et al., 2016). This could explain the above-span effects of the (visuo)spatial processing task observed in Doherty and Logie’s (2016) investigation of verbal memory span, and in Experiments 1 and 5.

The use of visual mnemonics, or indeed any other ‘strategy’ is difficult to disentangle from other possible explanations. It is imperative that researchers are aware that participants may approach tasks in novel ways, particularly when designing experiments. However, as discussed in Chapter 1, strategies and mnemonics can be a dissatisfying interpretation of data patterns to those who favour simpler explanations, such as those provided by effects of cognitive load or interference. In a recent commentary on the interpretation of data in terms of mnemonics, Morey (2016) describes how while being mindful of potential strategic approaches to tasks
is important when designing experiments, overuse of post-hoc explanations centred around these ideas can result in findings that do not fit with one model or another being prematurely dismissed. We identified a potential for overuse of post-hoc explanations of performance in Chapter 3 due to the large number of potential approaches participants may have to visual patterns memory tasks, and the choice to switch back to verbal memory tasks was influenced by the possibility that the visual patterns task was particularly vulnerable to explanations based around the use of mnemonics.

The strongest evidence for the use of visual codes for verbal materials comes from studies that specifically manipulate the visual similarity of letters or words. Logie et al. (2000) compared the effect of the visual similarity of words and letters across a number of experiments, and found small costs/benefits of visually similar/dissimilar stimuli. Saito et al. (2008) expanded upon these findings with further evidence for visual coding of verbal materials through the use of Japanese kanji characters which allow orthogonal manipulation of phonological and visual similarity. Again, these effects were small, but they were shown to be independent from verbal coding by their resilience to articulatory suppression. More recent evidence of the use of visual codes in retaining visually presented verbal sequences in English and in Japanese was reported by Logie, Saito, et al. (2016). Our procedure included no manipulation of visual similarity, so without extensive post-hoc data processing and analysis it is not possible to test whether participants relied more on visual codes in above-span conditions. However, the size of the effects reported in Saito et al. (2008) and Logie et al. (2000) effects suggest that while visual coding of visually presented verbal stimuli could have occurred it is unlikely to be the sole or primary cause of the above-span effects on memory accuracy.

The effect of AS in Experiment 8 could be interpreted in terms of reduced access to the phonological loop. It has been argued that auditorily presented verbal stimuli
have automatic access to the phonological loop, while visually presented stimuli do not (Colle & Welsh, 1976; Salame & Baddeley, 1982). As such, the addition of AS in Experiment 8 could have prevented recoding of visual material into phonological codes, resulting in reliance on other maintenance methods more susceptible to cross-modal, task-switching, or shared-resource interference. Logie et al.’s (1996) investigation of the generalisability of the word length and phonological similarity effects revealed differences in individuals’ demonstration of these phenomena (even though the analysis of the whole dataset found significant effects overall), and differences in the same individuals’ demonstration of these effects across different testing sessions. When counting the number of participants who failed to show word length or phonological similarity effects across visual and auditory presentation of stimuli, a higher proportion of participants failed to demonstrate the word length effect (or showed an effect in the opposite direction) compared to the phonological similarity effect. The word length affect is argued to be an artefact of the sub-vocal rehearsal system, with speed of sub-vocal articulation being linked to higher memory spans (Baddeley et al., 1975). Logie et al. (1996) found that the presence of a word length effect was positively correlated with span, but only for visual presentation.¹ This would suggest that those participants who did not demonstrate a word length effect were not relying on sub-vocal rehearsal, but on some other less effective maintenance mechanism. It is therefore possible that the above-span effects observed in the experiments reported here were due to participants’ increased reliance on less

¹It is possible to test for ‘Participant’ interactions using the multilevel regression analysis method reported in Chapters 3-6. We ran post-hoc analyses to investigate the possibility of these types of interactions in our data. These tests were always inconclusive, likely due to a lack of statistical power to detect such interactions with our sample sizes. Both experiments reported in Logie et al. (1996) used larger samples than the experiments reported in the preceding chapters, and asked participants to report any strategies that they adopted. The presence or absence of phonological similarity and word length effects was shown consistently only for those participants who reported using sub-vocal rehearsal. A reanalysis of their data could provide further evidence that participants approach tasks differently, and that differential encoding/rehearsal strategies predict memory span. For a recent reanalysis of the Logie et al. (1996) data see Wang, Logie, and Jarrold (2016)
effective non-phonological forms of memory maintenance. Unfortunately, since the procedures in Experiments 5-9 featured single-syllable letters for memory stimuli differences it is not possible to test this hypothesis with these data.

The proposal of a specific dual-task mechanism can also explain the processing load effects in terms of the MCM framework. As previous discussed, processing errors have been shown to capture attention (Laming, 1979; Jentzsch & Dudschig, 2009) and can account for ‘cognitive load’ effects when left unchecked (Lewandowsky & Oberauer, 2009). While the inclusion of the ‘processing errors’ predictor did not abolish processing load effects, in the discussion of the results it was acknowledged that it is difficult to separate processing load effects from the effects of increased error rates. Since co-ordination of dual-tasks is argued to be a function of the central executive component of working memory (Logie et al., 2004) or a feature of emergent executive function (Logie, 2016), the process and evaluation of increasing number of errors in the high load conditions could disrupt performance enough to elicit the observed above-span effects. The impact of errors could also result in participants prioritising the processing task over the memory task, resulting in drops in memory performance like those observed in Experiment 9. These effects could be additive to those described above.

**TBRS Model.**

The investigation of titrated spatial processing load on verbal memory span in Doherty and Logie (2016) provided data in stark contrast to previous TBRS findings regarding the effect of cognitive load on span (e.g. Portrat et al., 2008; Barrouillet et al., 2004, 2007). While verbal memory span appeared affected by above-span processing load (see Figure 2.2, page 45), the effect was not statistically significant. Coupled with the fact that dual-task spans did not differ from the single-task mea-
sure, these data provide a problem for a purely shared-resource working memory framework. Also, in the opposite pattern usually reported in the TBRS literature, Doherty and Logie’s (2016) analysis of processing accuracy and the analysis of processing accuracy in Experiment 1 suggest that it is processing performance that is sacrificed once the capacity of the verbal memory system is exceeded (although research following on from Barrouillet et al., 2004, 2007 has investigated costs to processing accuracy: see Vergauwe et al., 2014).

However, as discussed in previous chapters, Camos et al. (2009, 2011) demonstrated how cognitive load effects are larger under AS due to participants’ adaptive use of refreshing when sub-vocal rehearsal is not available. Experiment 8 was the only one to include AS and this revealed effects of concurrent processing load on memory accuracy for all list lengths. The fact that the number of processing items affects performance in all memory load conditions in Experiment 8, and for above-span lists in Experiments 5 and 6, suggests that participants rely more on the attention-based refreshing mechanisms for memory when phonological processes are unavailable or insufficient.

A ‘switch’ to refreshing mechanisms is further supported by the effects of above-span memory load on processing accuracy (observed in Doherty & Logie, 2016, and Experiments 1 & 5). The fact that RTs for the first processing item were longer for higher memory loads also supports this, replicating the same effect argued by Vergauwe et al. (2014) to be a result of recruitment of attention-based resources to ‘refresh’ decaying memory traces.

Overall the results from the presented experiments are consistent with recent research into the TBRS model (primarily those discussed above: Camos et al., 2009, 2011; Vergauwe et al., 2014). The above-span effects replicated across the experiments are the first to demonstrate that memory load dictates whether participants’
7.2. Interpretation within the context of MCM and TBRS frameworks

rehearsal is phonological or refreshing based. The fact that above-span performance with no AS so closely resembles the processing load effects observed across all list lengths further supports this, as participants relied on refreshing under AS (Experiment 8; Camos et al., 2011) or when memory load exceeds their phonological capacity (Experiments 5 & 6).

However, it may not be the case that the attention-based resource involved in maintenance of above-span memory loads or recruited when the availability of specialised verbal rehearsal processes are blocked by AS is the ‘refreshing’ mechanism described in the TBRS literature. In the previous section a criticism of mnemonic or strategy explanations of performance was that it provided un-testable or un-refutable accounts of data. A related criticism of the ‘refreshing’ explanation is that it may be over-specified based on the current body of evidence in the literature. Refreshing is described as an extremely quick process: Vergauwe et al. (2014) proposed ~50ms per item. Therefore, the efficiency with which refreshing can occur would presumably make more time consuming mechanisms such as sub-vocal rehearsal obsolete. On this argument, it would therefore be unlikely that participants’ ‘default’ rehearsal mechanisms would be the less time-effective method of sub-vocal articulation. The fact that phenomena relating to phonological-based storage and rehearsal are so prevalent in the literature, coupled with the data presented here suggesting at-span and below-span performance relies on sub-vocal processes, strongly supports the argument that participants’ ‘default’ method of rehearsal would be the least effective at combating the time-based decay according to the TBRS model.

As discussed in the General Introduction (‘Difficulties in comparing working memory models’, Section 1.2, page 29), efforts by Vergauwe et al. (2016) to detect serial refreshing were unsuccessful, requiring an interpretation of the authors’ results that relied on a re-evaluation of the refreshing mechanisms that was largely
7.2. Interpretation within the context of MCM and TBRS frameworks

incompatible with core assumptions of the TBRS model. Referring again to the speed of refreshing outlined in Vergauwe et al. (2014) and reiterated in Vergauwe and Cowan (2015), it seems highly unlikely that the procedure of Vergauwe et al. (2016) would be able to predict serial position effects by probing memory at different time frames. If the ‘cost’ of completing refreshing of a whole list would be a matter of milliseconds, why would one expect that probing memory would result in an immediate halt to refreshing? In addition to this, Vergauwe et al.’s (2016) post-hoc hypothesis that refreshing of items may be occur in parallel, while being inconsistent with the TBRS model’s assumption of an attention-based bottleneck (Barrouillet et al., 2004, 2007), is also incompatible with Vergauwe et al.’s (2016) interpretation of the effect of memory load on processing RTs which is described as a linear effect due to the additional time to serially refresh each additional item.

The initial arguments for refreshing were based on brain imaging evidence for a separation of refreshing and rehearsal processes (Raye et al., 2002, 2007). However, the ‘refreshing’ instructions given to participants were simple to ‘think of’ a recently presented word, compared to sub-vocally repeating the word. These same instructions were used by Camos et al. (2011) when contrasting refreshing and sub-vocal rehearsal mechanisms. While acknowledging the aforementioned potential pitfalls of relying on post-hoc interpretation of participants’ approach to tasks, it is important to consider that the instruction to ‘think of’ words does not encourage any processes (such as seriality) that were then argued to be features of this mechanism. Participants could equally have pictured the object described by the word, visualised the typed word, or attached some semantic label to the word. Following the theoretical leap from Raye et al.’s (2002, 2007) initial description of refreshing to the fully realised mechanism described in subsequent TBRS research, the process of refreshing has become a primary focus of the model. We would argue that while the effect of
cognitive load is well established, the TBRS model’s attribution of the cause of this effect to refreshing is premature due to the above criticisms.

Summary of MCM and TBRS interpretations.

Both the Multiple Component and TBRS models can provide an explanation of the above-span effects on memory and processing accuracy. The hypothesis of domain-general effects for high load tasks provided by Logie (2011), previous evidence for the use of visual codes (Logie et al., 2000; Saito et al., 2008; Logie, Saito, et al., 2016), the potential effects of increased errors or increased capture of attention on a specific dual-tasking ability (as proposed by Logie et al., 2004), could separately or in combination explain why memory accuracy is affected by concurrent processing for above-span lists. Despite the similarities in MCM and TBRS theories, the use of visual codes is something that is unique to the former model. Future research conducted as part of the adversarial collaboration discussed in the following pages intends to focus on this difference when contrasting these models.

While research into the TBRS model has established that participants utilise different rehearsal mechanisms based on whether or not access to the phonological loop is blocked by AS (Camos et al., 2009), these data demonstrate how participants rely more heavily on attention-based resources once their verbal memory capacity is exceeded. These findings therefore expand upon previous TBRS research, and the above-span processing load effects observed in the presented experiments could aid further understanding of the cognitive load effect. However, Doherty and Logie’s (2016) investigation of memory span demonstrated that once concurrent processing load is set according to participants’ individually measured abilities the effect of cognitive load on span disappears (or at least the effect is reduced in magnitude to the point where it is undetectable using a commensurate sample size). The above-span
effects on memory accuracy observed across a number of our experiments are also considerably smaller than the cognitive load effects reported in the TBRS literature, and is always far smaller than a single-item increase in memory load. Therefore, our findings suggest that titrated demand reduces the overall effect of cognitive load, but that this effect can still be detected when the working memory system is under high load.

As discussed, while the cognitive load effect has been replicated a number of times the exact nature of the TBRS refreshing mechanism is less clear. Likewise, while a number of interpretations and explanations can be provided by the MCM, these are difficult to disentangle and would require additional experiments to identify. What is common between both models’ explanations is that some ‘other’ process besides subvocal rehearsal can be utilised to maintain verbal memory traces in the short-term. Whether this mechanisms is one or all of the candidates from the MCM, or refreshing as described by TBRS, it is clear that reliance on this additional process or set of processes is recruited when access to the phonological loop is blocked (Experiment 8; Camos et al., 2009) or when verbal memory capacity is exceeded (Doherty & Logie, 2016; Experiments 1, 5, & 6). Whatever mechanism is involved, the ‘cost’ can be observed in the concurrent processing tasks’ accuracy (Experiments 1, 5, and 7) and RTs (Experiments 6-8, and Vergauwe et al., 2014).

7.3 Interpretation within the context of other theories of working memory.

Chapter 1 focussed on the MCM and TBRS theories since these were the models used to generate hypotheses, due to both models assuming time-related decay of memory traces but differing in their proposed mechanisms and underlying structure of work-
7.3. Interpretation within the context of other theories of working memory.

ing memory. While our procedures were designed to contrast multiple component and resource sharing accounts of working memory, our findings could be interpreted in a number of ways.

A selection of relevant theories and their likely explanation of our findings are summarised here. This list is by no means exhaustive as a far larger number of theories exist within the working memory literature. Our selection of models for discussion was informed by the categories described in Oberauer et al. (2016) to cover different theories of short-term forgetting, but as also based on our aim to demonstrate that our findings are relevant for a number of working memory theories and fit with their likely predictions regarding participants’ performance at above-span memory loads. While the theories discussed here all differ in their description of the structure and functional limits of working memory, each can provide an explanation of what the ‘extra’ resource supporting memory performance could be in our experiments. The possible rehearsal or maintenance methods employed during dual-tasking could be one or some combination of those suggested, and future research to compare and contrast these mechanisms could lead to the development of a unified theory of working memory.

Primary and Secondary Memory.

In Chapter 1 we discussed Unsworth and Engle’s (2006) review of the simple and complex span literature. The authors found that the correlations between fluid intelligence and performance on simple span and complex span tasks converge on a similar value so long as the former task used long item lists. The authors noted that a review of the literature revealed that simple span performance relied more on phonological processes, as evidenced by its vulnerability to interference from AS, phonological similarity, and word length effects. Complex span was argued to rely
7.3. Interpretation within the context of other theories of working memory.

both on phonological processes, but also on additional processes that contribute to the correlation with measures of complex cognition.

These additional processes are said to be a transfer of information from ‘Primary Memory’ (PM) to ‘Secondary Memory’ (SM). Single-tasks such as simple span can rely on PM (which is said to be limited to around four items: Unsworth & Engle, 2007), but during dual-tasks like complex span items are displaced from PM into SM. Retrieval from SM is described as a search process that is made more effective by limiting activation of irrelevant information. SM memory search is made more difficult as proactive interference builds with increasing set sizes, if memory items are improperly encoded, and because of interference at retrieval. The reason that simple span measures of memory that utilise long lists of items correlate with fluid intelligence is therefore due to the need to transfer items to SM when the capacity of PM is exceeded. The correlation of simple span with long lists and complex span with higher order cognition is therefore driven by individual differences in the ability to utilise SM.

Interpreting our results in terms of Unsworth and Engle’s (2007) description of the roles of PM and SM in dual-tasking, it is clear that high memory load conditions would require greater use of SM. At shorter list lengths participants may be able to store a greater number of memory items in PM while responding to each serially presented processing stimulus, meaning that the total number of processing stimuli presented in the interval would not have a direct effect on memory accuracy. However, as participants’ memory capacity is exceeded (i.e. in the above-span conditions) more memory items would have to be transferred to SM. The cognitive load effect could therefore be reinterpreted as being the result of increased interference with the transfer and retrieval of memory items from SM, which could also be responsible for storage of processing task goals and lexical access.
The RT effects on first processing items suggest that longer lists require extra time in order to be transferred, and the higher density of processing stimuli in the high load conditions could further prevent transfer to SM. The fact that a greater effect of processing load is observed when access to the phonological loop is blocked by AS (Experiment 8; Camos et al., 2009) supports this interpretation as participants would have to rely on SM from the start since Unsworth and Engle (2007) argued that PM relies more heavily on phonological processes. When the presentation time for memory items was reduced in Experiment 7 it is possible that this affected transfer to SM (evident in the lower memory spans compared to Experiment 6), meaning that participants were not relying on SM and so were less vulnerable to loss of information in the transfer/retrieval process.

In summary, our data can be interpreted in terms of Unsworth and Engle’s (2007) PM and SM framework. Just like MCM and TBRS accounts, this explanation assumes some other process is involved when access to default storage methods are insufficient or infeasible.

**Focus of attention, phonological codes, and chunking.**

Cowan (2010) discusses a central capacity limit of working memory of ~3-5 items, once factors such as rehearsal and chunking are accounted for. It is therefore possible that participants supplement their phonological capacity with additional ‘slots’ from this central capacity store, and the addition of the secondary task takes up some of this ‘extra’ capacity and therefore affects memory performance. For example in Experiment 8 the absolute number of items recalled by participants in the dual task conditions was between 50-60% of their single-task span and decreased with high processing loads. Conversely, in Experiment 6 where participants were free to utilise sub-vocal rehearsal the number of items recalled is higher, but also does not appear
7.3. Interpretation within the context of other theories of working memory.

to be affected by increases in processing load (Figure D.1 in Appendix D).

Z. Chen and Cowan (2005, 2009) propose contributions of both phonologically-based codes and long-term memory (LTM) ‘chunking’ to verbal memory span. The authors suggest that a verbal capacity of seven items could result in contribution from both code-specific and domain-general systems, and that each system be relied upon more heavily depending on task demands. Z. Chen and Cowan (2005) investigated participants' memory for pre-learned pairs of words (i.e. ‘chunks’: Miller, 1956) compared to single items. Z. Chen and Cowan (2005) found evidence for ‘chunks’ for twelve-word lists since six pairs could be recalled as well as six single items. However, the authors found that four pairs could be recalled as well as eight single items, suggesting a limit based on the absolute number of items. Z. Chen and Cowan also found that participants’ performance suggested chunk-based limits in free recall but item-based limits in immediate recall. The authors propose that phonological representations contain more detail and order information, while the ‘chunk’ representation has a higher absolute limit that can benefit from restoration or redintegration of memory traces.

Z. Chen and Cowan (2005) found intermediary effects for mid-length lists, and suggested that participants could be using both phonological and chunking strategies, or that participants rely on phonological representations when the capacity of said store is sufficient. This would explain why chunking is observed for lists that should exceed the capacity of the phonological store. In a follow-up study, Z. Chen and Cowan (2009) investigated verbal memory performance under AS for single words and pre-learned word pairs in order to isolate the contribution of activated-LTM. The authors found evidence for a constant capacity of about three ‘chunks’ across all list lengths when access to phonological codes was blocked by AS and when serial order accuracy was not scored. Z. Chen and Cowan (2009) also found that during
7.3. Interpretation within the context of other theories of working memory.

Free recall participants recalled words that had previously been part of the same ‘chunk’ together, compared to items from the single-item conditions.

An interpretation of our findings in terms of phonological codes and chunking in LTM would be very similar to the PM and SM (Unsworth & Engle, 2007) explanation. Participants rely on phonological codes for shorter lists, but when this capacity is exceeded they rely on some form of activated-LTM. Our verbal memory stimuli were all randomly generated lists and so present no possibility of learning over the course of the experiment. However, it is still possible that participants either spontaneously begin to chunk items, offload them to LTM for later retrieval, or hold them in their activated-LTM/focus of attention. The above-span effects of processing load could therefore be interpreted as a symptom of increased reliance on these processes rather than sub-vocal rehearsal. Since the lexical decision task (Experiments 6-8) requires access to LTM, it is likely that when the verbal memory task requires access to activated-LTM there is increased interference between the two tasks. While the spatial processing task (Experiment 5) doesn’t rely on access to LTM to the same degree as lexical decisions, task goals and response requirements would need to be held in LTM and retrieved when needed. When access to the phonological loop was blocked by AS in Experiment 8 participants would have to rely on activated-LTM processes to a greater degree, explaining the presence of a processing load effect across all list lengths.

**Changing attention costs across the verbal rehearsal process.**

We have previously discussed Naveh-Benjamin and Jonides’s (1984) proposal of a two-stage process of maintenance and rehearsal of memory traces. The first stage of verbal memory maintenance in which rehearsal processes are ‘set up’ and initiated is said to be cognitively demanding, and could account for the large memory load
effects on first-item RTs in the processing task (Experiments 6-8; Vergauwe et al., 2014). The fact that dual-task verbal memory performance is resistant to ‘shifts’ of attention but is only affected when full priority is given to the concurrent task supports this (Experiment 9; Morey et al., 2013). The second ‘rehearsal’ stage is said to be less cognitively demanding, which is supported by research showing small dual-task costs and the fact that RTs on subsequent processing items are less affected than the first item (Vergauwe et al., 2014 found smaller RT effects for subsequent processing items, while our effects were non-significant Experiments 1, and 6-8).

In terms of how these effects could explain our dual-task effects, the cost to processing RTs for each additional memory item could be interpreted as an increased attentional load (or ‘set up’ cost) for longer lists. For memory performance, the shorter presentation time in Experiment 7 should presumably reduce participants ability to initiate rehearsal mechanisms and therefore result in poorer dual-task performance, but participants were mostly unaffected by concurrent processing load. It is possible that since span was calculated with shorter presentation times that the effect was ‘titrated out’, in that spans were calculated up until the point participants could sufficiently initiate rehearsal processes to combat decay: their ability to dual-task under these conditions is therefore evidence of effective use of these processes due to the small demand required during the sub-vocal rehearsal stage. Performance in Experiment 8 is predictably poorer due to participants’ inability to utilise sub-vocal rehearsal, and the additional processing load cost could be due to participants increased use of attention to maintain memory traces. The above-span effect observed in Experiment 6 would be combination the effects in Experiments 7 and 8: participants’ are able to initiate rehearsal with a cost to first-item processing RTs, but once list lengths exceed their capacity the attentional demand of the processing task impacts memory performance.
7.3. Interpretation within the context of other theories of working memory.

**Serial Order in a Box (SOB).**

In contrast with decay-based theories such as MCM and TBRS, some researchers argue for purely interference based forgetting. Lewandowsky, Geiger, and Oberauer (2008) described the ‘Serial Order in a Box’ (SOB) model as assuming that all forgetting is due to automatic encoding of novel stimuli. In a series of experiments, the authors demonstrated that repeating the same distractor did not have a disruptive effect on memory performance while repeating a number of different distractors did affect performance on the memory task. Lewandowsky et al. describes this ‘novelty-sensitive’ encoding as the process in which items are encoded to the extent to which they differ from what is already being held in memory.

In the context of our experiments, each newly presented word/nonword in the lexical decision task would have privileged access to memory, and would interfere to a greater degree due to the overlapping representations of the two sets of verbal stimuli. However, within the context of purely interference-based forgetting, it is unclear why the lexical decision task would only affect memory performance in the above-span condition in Experiment 6. While the lexical decision task had some overlap in representation with memory items and so would be predicted to have an interfering effect on memory performance, the fact that the same pattern of above-span memory performance was observed with a spatial processing task in Experiment 5 is a problem for SOB. Likewise, SOB doesn’t provide a clear interpretation of why different patterns of performance would be observed using the same tasks but shortening the presentation time of memory items (Experiment 7) or with the addition of AS (Experiment 8).

An updated version of the SOB model, named SOB-CS (CS: complex span), was proposed by Oberauer et al. (2012). This incorporated a redintegration mechanism influenced by the TBRS model’s findings regarding cognitive load and refreshing.
7.3. Interpretation within the context of other theories of working memory.

However, because SOB-CS does not consider decay as being responsible for loss of memory traces (Lewandowsky & Oberauer, 2009; Oberauer & Lewandowsky, 2014), the role of this restoration process is to reduce the impact of interference by removing distractors from memory. Oberauer et al. (2012) provide an example of how removing distractors would benefit cognition, in which calculating the product of 24 and 3 would likely involve multiplying 20 and 4 by 3 separately, then adding the answers together (20 + 12). During the final step it would be not be necessary to keep ‘3’ in memory, and indeed removing this item from memory would prevent interference with the process of calculating ‘20 + 12’.

Interpreting our results within the context of the SOB-CS model, our above-span effects could be due to the larger number of distractors in the high processing load conditions but also a compounding effect of increased error rates. Oberauer et al. (2012) report a simulation showing that the effect of cognitive load is related to the amount of free time between processing items, rather than the duration of the item. If memory performance is linked to participants’ ability and opportunity to remove distractors from memory, it is possible that perseverating on distractors for which an erroneous response has been made could prevent its removal from memory. Considering the effects of processing errors observed in our experiments (Experiments 6-8) and in Lewandowsky and Oberauer (2009), it is possible that the above-span effects are due to participants having insufficient time to remove distractors from memory to combat interference effects.

The reason that processing load effects were larger in Experiment 8 could be due to the fact that AS during encoding means that memory items were vulnerable to interference from the start. During the dual-task conditions the larger effect of processing load would be symptomatic of these weak encodings. However, Experiment 7 poses a problem for the model. According to SOB-CS (Oberauer et al., 2012), the
shorter presentation times for memory items in Experiment 7 would result in weaker encoding and would explain the lower calculated spans. However, unlike Experiment 8, processing load effects in the dual-task conditions were small or non-significant. Oberauer et al. (2012) notes that while the SOB-CS computational model at present does not include a rehearsal mechanism, the authors state that they remain open to the possibility of a mechanism that strengthens memory traces if new data support its inclusion. Our observation of a specific above-span effect of processing load when memory load exceeds participants’ span (Experiment 6) and that this effect is present across all list lengths when sub-vocal rehearsal is prevented by concurrent AS (Experiment 8) could be argued as support for the inclusion of a specific verbal rehearsal mechanism in SOB-CS.

7.4 Difficulties in comparing working memory models (continued).

In Chapter 1 we discussed three main difficulties encountered when comparing models of working memory:

1. over-flexibility of models that allow assimilation of new research findings
2. data interpretation within the context of a single model, neglecting others
3. experiments designed to detect expected effects in a model

By designing our experiments to contrast MCM and TBRS theories, we strived to avoid (3). Calibrating dual-task demand according to participants’ single-task abilities was aimed to incorporate previous research showing small dual-task costs (Duff & Logie, 1999, 2001) and the importance of task titration (Cocchini et al., 2002; Logie et al., 2004). The reported experiments replicated cognitive load effects, but only when
participants’ working memory capacity was pushed to its limits. In line with previous work showing differential engagement of attention- and phonologically-based processes (Camos et al., 2009, 2011) above-span effects were found to be dependent on participants having equal access to both forms of maintenance, and biasing participants towards one process or the other changed the presentation of the cognitive load effect in line with TBRS predictions. Influenced by anonymous reviewers of Doherty and Logie (2016), Experiment 9 investigated a possible confound in our procedure in which participants may have been focussing on one task or the other, or paying insufficient attention to the processing task to elicit a reliable cognitive load effect. We observed data compatible with previous findings suggesting small involvements of attention during the rehearsal process (Morey et al., 2013). However, since our experiments were designed with two specific working memory models in mind they were still biased to detect phenomena predicted by these theories.

Points (1) and (2) have been addressed in this chapter, which attempts to interpret our findings within the context of not only the MCM and TBRS frameworks but also other theories. Providing interpretations to combat potential pitfalls of (2) has effectively demonstrated (1): most models discussed here can account for some or all of the effects observed in our experiments.

**Possible solutions.**

Being aware of the difficulties described above is important when designing and interpreting behavioural experiments. Researchers are unavoidably directed by their own interpretations of working memory, which are likely based on their own established procedures, methodologies, and observations. However, keeping in mind the assumptions of other models can prove useful when attempting to design experiments that will stand up to scrutiny under peer review, but also provide data that
can be interpreted by competing theories (e.g. providing adequate control conditions, comparable manipulations to previous research etc.).

**Open science.**

Researchers are expected to be open with their findings, co-operating with other researchers’ in their requests for data or materials etc. Recently there has been a greater emphasis in Psychology for open science practices, with services like the Open Science Framework (OSF, http://osf.io) providing an avenue for preregistering studies, hosting materials and data, and allowing open collaboration between researchers. By making materials and data open, researchers can invite interpretation and reanalysis of their data from others in their field. Fostering a sense of open collaboration may help researchers design experiments that they know will test more than just their own hypotheses, and could prevent theorists becoming entrenched in their own positions.

**Adversarial collaboration.**

Adversarial collaboration is an approach to research that requires that all involved parties agree on aspects of an experimental design beforehand in order to differentiate between alternative hypotheses. Mellers, Hertwig, and Kahneman (2001) report an example of such a collaboration investigating competing theories on the ambiguity of the word ‘and’. The two theorists Hertwig and Kahneman enlisted the help of Mellers to act as an arbiter for the study.

We have recently begun work on such a project, titled ‘Working memory across the adult lifespan: An adversarial collaboration’ (abbreviated to WoMAAC, Logie, Cowan, Barrouillet, Camos, & Naveh-Benjamin, 2016). Initially inspired by discussions between this author, Logie, and Barrouillet and Camos regarding the work presented in this thesis, the project has developed into a comparison between the Mul-
Multiple Component (Logie, 2011), TBRS (Barrouillet & Camos, 2014), and activated-LTM (Cowan, 2005) models. So far focus has been on developing procedures and analysis plans that can differentiate between the competing theories, with an aim to develop new theories or hypotheses based on findings. Data and materials will be made open allowing reinterpretation and reanalysis of project data by advocates of other models of working memory.

While this suggestion is not a feasible approach for all studies, the concept of ‘adversarial collaboration’ can help avoid some of the previously discussed pitfalls by requiring an in depth design process that takes into account different theoretical starting points. Of course, interpretation of results may still lead to disagreement: Mellers et al. (2001) featured separate interpretations and discussions from Hertwig and Kahneman, who despite arbitration failed to reach a consensus. The authors do agree that a benefit of the adversarial collaboration model is that parties are made more aware of the limitations of their claims. Based on their own experiences, Mellers et al. (2001) also make a number of suggestions, including participants in the collaboration considering beforehand what outcomes would change their mind, and should provide a-priori interpretations of unexpected effects. While these suggestions are particularly relevant to adversarial collaboration, such an approach to research in general could be invaluable when designing experiments that aim to contribute to scientific understanding rather than perpetuate debate.

7.5 Final summary and conclusions

Working memory, like many fields, is characterised by debate. A number of theories exist, but the differences between these theories may be more apparent than real. Over a number of experiments we have presented data consistent with the hypothesis that multiple-component working memory under high load may function as
would be expected under a domain-general resource (Logie, 2011). Recent research into the TBRS model has focussed on the alternative recruitment of phonological or attention-based rehearsal mechanisms depending on the availability and suitability of each (Camos et al., 2009, 2011). Our findings expand this research by demonstrating how participants rely on ‘default’ attention-free phonologically-based rehearsal when memory loads are set within their verbal memory capacity, but switch to some form of maintenance that requires the same attentional resource responsible for concurrent processing during high demand dual-tasking conditions. The effect of this switch to an alternative approach to memory maintenance is observed both in costs to memory performance and to concurrent processing accuracy and RT. There exist a number of possible candidates for this additional memory support, including visual recoding (Logie et al., 2000; Saito et al., 2008; Logie, Saito, et al., 2016), refreshing (Barrouillet et al., 2004, 2007; Barrouillet & Camos, 2014), or attention and activated-LTM (Cowan, 2005; Z. Chen & Cowan, 2005, 2009). Future research should focus on experimental manipulations aimed at differentiating between competing theories, and identifying the differential processes involved in maintenance of below- and above-capacity lists.
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Appendix A

Visual memory stimuli.

Below are example stimuli for each level of the visual memory task used in Experiments 2, 3, and 4. Patterns were based on those used by Logie and Pearson (1997).
Appendix B

Procedure for generating predicted probabilities.

The procedure for creating plots such as Figure 3.1 (page 80) involved using the ‘predict’ function in R. We create a new column in the data frame containing predicted values generated for each trial (taking into account memory and processing load condition, as well as the value of any other variables such as the number of processing errors made). These values are converted into probabilities and plotted over the bootstrapped data: for the sake of clarity only lines are plotted. Example code is given below.

```r
# Logistic Regression
Memory_Reg <- glmer(cbind(nCorrect, nErrors) ~ (MemLoad+ProcLoad)^2 + ProcErrors + (1|Participant),
                    data = DATA, family = binomial)

# Create Predicted Values Column
predicted <- predict(Memory_Reg, newdata = DATA,
                     type = c('link', 'response'))

DATA$Predicted_Log <- predicted
DATA$Predicted_Prob <- exp(DATA$Predicted_Log)/(exp(DATA$Predicted_Log)+1)
```
Appendix C

Words and nonwords for verbal processing task.

English words were generated from the MRC Psycholinguistic Database (Coltheart, 1981) online tool (http://www.psych.rl.ac.uk). The only parameters that were manipulated in the generation of the word list were ‘Familiarity’, ‘Concreteness’, and ‘Imagability’: each were set at minimum and maximum values of ‘500’ and ‘700’. Nonwords were generated from the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002) online tool:


Options ‘Only orthographically existing onsets’, ‘Only orthographically existing bodies’, ‘Only legal bigrams’, and ‘Morphologically ambiguous syllables’ were all set to True. Both words and nonwords contained 3-6 letters.

The complete sets of words and nonwords are listed over the next two pages.
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Nonwords

arned daid frind gwintz nirs rhird snops swirs uumped zarned
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bewed dealed frux gwocs mpped rhonts smurst swoost vance zeped
bews deaned froyes gwokes onde rlups smyst swuft vapse va
bhaft deened fruit gwived onze rintz snauze tade vaiae zeered
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Appendix D

Memory accuracy in Experiments 6 & 8 as a proportion of span.

This Appendix contains plots showing the number of memory items recalled as a proportion of span. Figure D.1 shows that performance was generally higher with no AS (Experiment 6), and appears less affected by concurrent processing load. Experiment 8 shows overall lower performance, but also a clearer effect of processing load on accuracy. Interpreting these results in terms of a discrete number of ‘slots’, performance under AS is more affected because participants must rely more on a central capacity rather than specific phonological-based storage/rehearsal.
Figure D.1: Mean memory accuracy as a proportion of span (with standard errors) across each combination of memory load (ML) and processing load (PL) in Experiments 6 (left) and 8 (right).