Identifying the Functional Architecture Underlying Multiple Representations in Visual Working Memory

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ABSTRACT

This thesis aimed to investigate how visual working memory takes advantage of long-term knowledge in order to allow semantic elaboration in the form of chunking and the role of the central executive in this process. Two leading theoretical frameworks of working memory which both emphasise the role of long-term memory are discussed. One of which views working memory as consisting of multiple discrete, modality specific subsystems (Baddeley, 2000) and one which views working memory as an activated subset of long term memory (Cowan, 2005). Both of these models propose the integration of short- and long-term representations to be attentionally demanding. To investigate this assumption, two forms of visual matrix pattern were generated; a high semantic set which lends itself to long-term memory support and a low semantic set which does so to a lesser extent. The initial block of empirical work aimed to establish the characteristics of the patterns sets. Superiority for the high semantic patterns was observed in terms of greater stability across increasing maintenance intervals. The benefit of increased presentation time was also shown to be greater for the high semantic pattern set indicating the importance of time in the semantic elaboration process. A second block of studies was then conducted to identify the implications of the two patterns sets for the functional architecture of working memory. In a secondary interference paradigm the pattern sets were shown to be differentially dependent on visual and verbal interference with low semantic patterns negatively affected by visual and not verbal interference and the opposite pattern observed for high semantic patterns. The use of executive and attentional interference paradigms demonstrated two levels of binding. Firstly, when attentional resources were continually captured by a secondary task, a degree of chunking was observed for both pattern sets, this is discussed in terms of *passive binding* on the basis of long-term knowledge in the absence of executive resources. In the absence of interference, effortful elaboration of the pattern sets is observed and this is greater for the high semantic patterns. This is discussed in terms of *active binding* with the involvement of executive resources. These findings are then discussed in terms of both the Cowan (2005) and Baddeley (2000) models and recent observations made by Baddeley et al (in press) to support a modification of the episodic buffer in Baddeley’s model to allow for both passive and active binding and how this leads to striking similarities between the two theoretical perspectives.

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AUTHORS DECLARATION

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work.

Name:

Signature:

Date:

AIMS OF LITERATURE REVIEW

The work of Phillips and Christie (1977a; 1977b) suggests that in serial visual recall, there is a one-item recency effect representative of a single visual pattern being held in an online pre-categorical format with pre-recency items being stored offline in a categorical form, allowing for above-chance recognition performance. A central question in this thesis is concerned with how visual representations of a single pattern involving different degrees of semantic support are represented in working memory in the absence and presence of within and cross modality interference and how this can be accommodated by current models of working memory.

The first two chapters in the current thesis will review two theoretical perspectives of working memory. The first of which considers working memory as consisting of multiple components, with a focus on modality specific slave systems. The second theoretical perspective is one which developed in parallel but considers working memory as activated long term memory and focuses on executive control processes. The focus of these chapters will be on visual working memory, its interface with long term memory and in particular how each model can accommodate findings from studies employing novel matrix patterns. A third review chapter will then discuss the nature of binding together multiple representations in working memory. Looking at the binding together of low-level visual features (within-modality) and the binding of high-level long-term knowledge with temporary phonological information in memory for prose and what research into visual matrix patterns can add to this body of literature.

CHAPTER 1

Multi-Component Models of Working Memory

1.1. Chapter Overview

The current thesis reports a series of experimental studies investigating the integration of multiple representations in visuo-spatial working memory. This chapter aims to summarise the development of multi resource models of working memory since the original conception almost 40 years ago. This will be achieved by providing a skeletal view of the Baddeley and Hitch (1974) model of working memory and an outline of the evidence that resulted in the models proposal. This will be built upon leading to explanation of more recent conceptualisations, providing the greatest emphasis on processes and components most pertinent to the current thesis. Specifically, visuospatial working memory, the processes involved in the integration of multiple representation in working memory and a review of how this can be accommodated within multi-component models.

1.2. Early Conceptualisations of the Multi Component Models of Working Memory

The early modal models of memory (e.g. Atkinson & Shiffrin, 1968) suggested that there are separate subsystems of memory, comprising of a collection of sensory stores such as iconic and echoic memory from which information is transferred into a short term store (STS) via selective attention. Information within the STS was thought to rely heavily on a verbal code and was thought to be subject to rapid decay. As such rehearsal is required to maintain it and transfer it into a Long Term Store (LTS) which was in turn thought to rely heavily on semantic coding and have a potentially unlimited capacity.

This model, although providing a relatively simple framework for research, encountered several criticisms. For example, the view of the STS as a rehearsal and control process for the LTS was challenged by cases of patients with brain damage such as KF (reported by Warrington & Shallice, 1969) who demonstrated verbal STM deficits yet had apparently normal LTM abilities.

Studies demonstrating a recency effect in free recall tasks led Baddeley and Hitch (1974) to propose that a defining characteristic of short term memory is its limited capacity. They tested the function of short term memory by asking participants to maintain a number of digits while concurrently performing comprehension, reasoning and long-term memory (LTM) tasks, and found that even a digit load of six items didn't impair performance on the other tasks dramatically. They proposed that the component of working memory used for the reasoning, comprehension and retrieval tasks was separable from the store used for digit span. There was also a body of research proposing that short term recall was poorer for similar sounding material (e.g. Conrad & Hull, 1964; Wickelgren, 1966), which was termed the phonetic similarity effect. Baddeley and Hitch (1974) proposed this to be another characteristic of short term memory and as such tested the role of the STS in reasoning and comprehension using the phonetic similarity effect, and found that reasoning and comprehension performance was worse when the stimuli sounded alike but that this effect was also quite small. They finally used concurrent articulation to impair STM (as demonstrated by Murray, 1965) and showed slight impairment in reasoning and free recall. They used this evidence to suggest that comprehension, reasoning and recall from LTM do rely on a verbal STM, but that the small effects observed are representative of these tasks employing another component as well.

Baddeley and Hitch proposed this verbal Short Term Store to be one component of a *working memory* which served as a cognitive *workspace*, and they went on to develop a tripartite model of its functioning (1974; Baddeley, 1986; Baddeley, 1990). The first component, the *Phonological Loop* (PL), was suggested to be responsible for maintaining verbal and acoustic information in a passive phonological store and for refreshing these representations via the *Articulatory Loop*.

Figure 1.1. Simple representation of the working memory model proposed by Baddeley and Hitch (1974). Comprising and attentional control system (the CE) supported by two slave systems, one visuospatial and one verbal

The second component, the *Visuo-Spatial Sketchpad* (VSSP) was proposed to be responsible for setting up and manipulating images (Baddeley, 1990). Finally, the *Central Executive* (CE) was presumed to be responsible for attending to and coordinating information and using representations stored in the two ‘slave systems’ to help perform complex cognitive tasks such as reasoning and comprehension.

Initially a large amount of the research into this model focussed on whether there are separable, modality specific slave systems (i.e. verbal and visuo-spatial). To test this, Baddeley, Grant, Wight and Thompson (1975) used the Brooks matrix task (Brooks, 1968). In this task participants are asked to imagine a 4 x 4 grid. They are then required to learn a sequence of sentences that are either spatial or non-spatial. For example, a spatial sentence would be “in the next square on the right put a 5”, whereas a non-spatial would be “in the next square to the quick put a 3”. It is presumed that in the spatial condition, participants are able to use imagery to aid recall of instructions. When performed along with a concurrent visuo-spatial tracking task, Baddeley et al (1975) found that tracking impaired performance on the imagery (spatial) version of the Brooks task and had no effect on the non-imageable (verbal) condition, therefore supporting the notion that there is a system in operation that was separable from that responsible for verbally coded material. Subsequent research has demonstrated similar findings. For example Smyth, Pearson and Pendleton (1988) used short term memory tasks to test the functioning of the VSSP. They found that concurrent spatial tasks impair memory for movements or for sequences of spatial locations on the Corsi blocks tasks (a measure of spatial span), whereas concurrent articulation did not impair memory for locations, again supporting the claim for separate visuo-spatial and verbal temporary storage systems. Quinn and McConnell (1996a; 1996b, 1999) used an irrelevant visual information technique called Dynamic Visual Noise (DVN; discussed in detail in chapter 8) and showed it to consistently disrupt visual imagery performance but have no effect on verbal tasks. This lends itself quite readily in support of discrete buffers for verbal and visuo-spatial representations.

1.2.1 The Phonological Loop

In the earlier phases of the models development a large amount of the research effort was also dedicated to exploring the phonological loop (PL). Active interference techniques have been used to characterise it as articulatory rehearsal processes maintaining representations in a passive store (Baddeley, 1997). Passive techniques such as irrelevant background speech have been used to characterise the representations stored in the phonological store with the assumption that speech has obligatory access to it. Such research has validated this assumption and in turn has provided support for a passive phonological store (e.g. Colle & Welsh, 1976; Salamé & Baddeley, 1982). Speech's obligatory access to the phonological store has been labelled the *irrelevant speech effect*. Colle and Welsh (1976) reported that hearing German speech impairs English speakers' immediate memory for numbers presented visually, suggesting interference with the digits in the PL. Further research of this sort has found several other consistent effects in verbal working memory. The *phonological similarity effect* was reported by Baddeley (1990, 1996), who showed that people generally have poor memory for similar sounding words, and that similar sounding items are harder to discriminate at recall. This along with the irrelevant speech effect refers to the functioning of the phonological store.

In contrast to the above, the following two effects are observed in the articulatory rehearsal loop. The *word length effect,* proposed by Baddeley, Thomson and Buchanan (1975) suggests that participants have better short term memory for words with fewer syllables. It is also observed that short term memory for words is limited by the rate at which such words can be sub-vocally rehearsed, typically limited to the amount a person can pronounce in 2 seconds (Baddeley, 1986). A final effect is that of *Articulatory Suppression*, which ties in with the previous effect, whereby if a participant is prevented from rehearsing the word by requiring them to say a simple word out loud, memory for verbal information is impaired. The phonological loop has been shown to be able to account for a wide range of laboratory based findings. It also appears to be implicated across a range of cognitive functions, including language comprehension (McCarthy & Warrington, 1987) language acquisition (Gathercole & Baddeley, 1993) and the learning of a second language (Baddeley, Papagno & Vallar, 1988).

1.2.2. The Visuo-Spatial Sketch Pad

Research into the nature of the VSSP initially focussed on identifying whether the representations in the sketchpad are predominantly visual (i.e. static visual representations) or spatial (defined by movements or sequences), typically employing imagery techniques. Baddeley and Lieberman (1980) reported that concurrent performance of a secondary spatial tracking task impaired performance on the primary task which was the imagery version of the Brooks Matrix Task (Brooks, 1968, presumed to be a general measure of VSSP), and in contrast a concurrent visual task (brightness judgements) had no effect. The authors went on to conclude that the VSSP was spatial in nature. However, Andrade, Kemps, Werniers, May and Szmalec (2002) suggest that this result may be better explained by poor choice of task. They point out that the Brooks matrix task loads heavily on spatial resources and so it would be expected that spatial interference would have a greater effect than visual interference. It must also be noted that subsequent studies have revealed negative effects of brightness judgements (Beech, 1984; Quinn, 1988) suggesting both visual and spatial processes contribute to imagery of the Brooks matrices. Baddeley et al (1975) proposed that the recall advantage for concrete nouns was dependent on the imagery function of the VSSP but then failed to demonstrate an effect of spatial tracking on recall of concrete nouns. However, later studies demonstrated interference of concurrent visual tasks on recall of imageable words (e.g. Logie, 1986; Matthews, 1983) proposing visual working memory supports this form of imagery.

As discussed above, Salamé and Baddeley (1982) showed memory for visually presented digits could be disrupted by the presentation of irrelevant spoken material (irrelevant speech effect). Logie (1986) showed a comparable effect for unattended visual material, where visually presented items cause substantial disruption to the Pegword mnemonic while unattended speech disrupts rote verbal memory. The pegword mnemonic is a mnemonic technique whereby participants are taught a list of pegwords, e.g. '*one is a bun, two is a shoe'* etc. When presented with a word list they are then instructed to imagine the word pictorially and integrate it with a designated pegword, for example if the first to-be-remembered word was *cat*, this would be integrated with the first pegword *bun*, and the participant would perhaps visualise a *cat in a bun*. Visual disruption occurs despite the fact that spatial demands of the secondary task are minimal and that the mnemonic in question is not one that places heavy demands on spatial coding, suggesting a separation of visual and spatial processing. Logie went on to suggest that the sketchpad is sensitive to both visual and spatial characteristics with the point of maximum vulnerability depending on the characteristics of the tasks involved. From a neurological perspective, Jonides et al (1993) demonstrated a neuroanatomical separation between performance on memory for shape (left hemisphere) and memory for location (right hemisphere). More recent research has further specified this with spatial working memory being associated with the dorsolateral pre-frontal cortex and the mediodorsal thalamic nucleus (Funahashi, Takeda & Watanabe, 2004) and visual memory being associated with the posterior parietal cortex (Todd & Marois, 2004).

1.2.3. The Central Executive

The Central Executive was possibly the least well understood and described component of the multi-component model of working memory and received a lot of criticism because of this. It was first conceptualised as a pool of general purpose processing capacities, including storage, however this idea was abandoned in favour of the view the central executive's ability to increase total storage capacity is a function of its ability to access LTM and other systems. Baddeley (1986; 1996) went on to suggest that the central executive is a system used purely for processing and performing functions such as selective attention, strategy switching, retrieval from LTM and dual task coordination. This view of the central executive is carried forward into Logie's model discussed below (1995; Baddeley & Logie, 1999). However, it remains unclear whether the central executive is a control system which performs all of the functions mentioned above, or whether it is a collection of equally important individual control processes which interact (and that overall control is simply an emergent property; Baddeley & Logie, 1999). The debate between the concept of a unitary versus a fractionated executive, and the available evidence, will be discussed in detail in chapter 4.

1.3. Recent developments in Multi-Component Conceptualisation

1.3.1. Logie and Visuo-Spatial Working Memory

Evidence for the VSSP has included research, such as that presented above, in which participants are explicitly instructed to generate, maintain and inspect conscious visual images and research which looks at the short term retention of visual and spatial information in the absence of explicit imagery instructions. The assumption has been that both types of evidence reflect the operation of the VSSP. However Morton and Morris (1995) report the case of a patient, MG, who performed poorly on mental imagery tasks yet retained normal performance on tasks involving the maintenance of visual and spatial information. Furthermore, Pearson, Logie and Green (1996) reported that spatial tapping and arm movements can be shown to disrupt performance of visual and spatial tasks but not mental imagery. Pearson (2001) suggests that imagery and visual storage may not be synonymous; Kosslyn and Shin (1994) suggested that imagery may be functionally distinct from the processes which underlie the short term retention of visual material in general. Both Pearson's and Kosslyn's conceptualisations of Visual working memory are discussed below. However, the majority of evidence presented in this section will be centred on tasks which look at the retention of visual and spatial information in the absence of explicit imagery instructions.

Research employing tasks which are more clearly spatial (e.g. the Corsi Blocks task, Smyth & Pendleton, 1989; Smyth and Scholey, 1994) or visual (e.g. Matrix Span; Della Sala, Gray, Baddeley, Allamano & Wilson, 1999; Logie & Pearson, 1997), has supported the view that there are separate visual and spatial processes in working memory. Logie and Marchetti (1991) showed that retention of spatial patterns but not visual information (colour hues) was disrupted by arm movements (involving spatial processes), whereas memory for visual information was disrupted by irrelevant pictures. A similar double dissociation was found by Della Sala et al (1999), using the Corsi blocks task (spatial) and the Visual Patterns Task (VPT, a visual matrix task), where it was found that irrelevant pictures disrupted memory for visual patterns and spatial tapping (tapping a set of keys in a designated sequence) disrupted memory for spatial sequences. Tresch, Sinnamon and Seamon (1993) also report dissociation between performance on visual and spatial tasks.

More recently Logie and Pearson (1997) looked at the pattern of memory development between ages 5 and 12, testing both visual and spatial span. Participants had to remember the location of the filled squares in a matrix for the visual task, and completed a derivative of the Corsi blocks for the spatial task; the measures were taken to be indices of the visual and spatial processes respectively. They observed that spatial and visual functions develop at distinct rates; this *developmental fractionation* pattern supports the fractionation of the VSSP architecture. Measures of the VSSP have focussed on memory for spatial movement and visual patterns and the research evidence above seems to point to dissociation between a capacity for retaining visual patterns and for sequences of movements.

The research presented above demonstrates that a range of visual and spatial secondary tasks interfere with a range of visual and spatial short term memory and imagery tasks, revealing a dissociation between spatial and visual processing, with several studies showing that spatial interference impairs spatial working memory more than visual working memory and vice versa (e.g. Della Sala et al, 1999; Hyun & Luck, 2007; Logie & Marchetti, 1991; Tresch et al, 1993; Woodman, Vogel & Luck, 2001; See Klauer & Zhao, 2004 for a contrasting view). More specifically a number of studies have indicated a disruptive effect of concurrent movement on the retention of spatial patterns (e.g. Baddeley & Lieberman, 1980; Logie, Zucco & Baddeley, 1990; Smyth & Pendleton, 1990) and a disruptive effect of viewing irrelevant, changing visual material on the retention of visual information (e.g. Logie, 1986; Quinn & McConnell, 1996a; 1996b). This could mean that there are separate visual and spatial systems in working memory each with its own storage and maintenance. However, Logie (1995; Baddeley & Logie, 1999) suggests that research of this sort represents the functioning of a visuo-spatial working memory (VSWM) system which retains pictorial and location information by a combination of spatial and visual processes. More specifically Spatio-Motor processes (the *Inner Scribe*) which help maintain or rehearse representations in a passive visual store (the *Visual Cache).* This view of VSWM parallels Baddeley's (1986) account of articulatory rehearsal processes and phonological store suggesting the two slave systems mirror functional architectures (See Pearson, 2006, for an alternative account).

Logie's (1995) revision of the working memory model differs from the original working memory model in one very important way. Logie (1995; 2003) proposes input occurs via activated LTM rather than the perceptual system, making working memory a *workspace* for activated LTM rather than a *gateway* leading from perception to LTM. There is growing support for the idea that the contents of working memory are interpreted (e.g. Beschin, Cocchini, Della Sala & Logie, 1997; Denis, Beschin, Logie & Della Sala, 2002).

It is important to note that this separation of visual and spatial processes in working memory has been categorised in several slightly different ways. As well as a distinction between a 'visual cache' and an 'inner scribe' the work discussed above showing dissociations between memory for visual matrix patterns and performance on the variants of the Corsi blocks task can also be explained in terms of memory for a static arrays versus memory for dynamic sequences of movements or pathways (Pickering, Gathercole, Hall & Lloyd, 2001) or passive versus active memory (Cornoldi & Vecchi, 2003).

Memory for sequences has been demonstrated to be more intimately linked with executive resources relative to memory for static visual arrays. Smyth and Scholey (1994) demonstrated a detrimental effect of shifting attention to identify the location of tones on recall of a sequence of movements. This effect was also observed when participants shifted attention without motor responses, including eye movements (Smyth, 1996). More recently research has showed similar effects on the Corsi block tasks when attention is shifted along with eye movements (e.g. Postle, Idzikowski, Della Sala, Logie & Baddeley, 2006).

As discussed above, Baddeley and Lieberman (1980) showed an effect of visual interference and arm movements on the imagery version of the Brooks Matrix Task and an effect of verbal interference on the verbal version of the same task. Salway and Logie (1995) also demonstrated this effect, but also required participants to perform a concurrent random number generation task (RNG). RNG involves participants generating sequences of random numbers and has been shown to be demanding of executive resources (Vandierendonck, De Vooght & Van Der Goten, 1998). Salway and Logie showed that RNG had a greater effect on the spatial Brooks task than on the verbal Brooks task, suggesting that perhaps spatial working memory draws more heavily on executive resources (a notion supported by several authors e.g. Miyake, Friedman, Rettinger, Shah & Hegarty, 2001).

Rudkin (2001) showed that memory for sequences on a task similar in demands to the Corsi blocks task was disrupted by RNG. The authors then went on to employ Random Interval Repetition (RIR). RIR requires participants to respond as quickly as possible to a randomly emitted signal, this is designed as a non-spatial task which requires executive control (Vandierendonck et al, 1998). Rudkin (2001) showed RIR disrupted memory for locations of a sequence of emitted tones, supporting the idea that executive control appears to disrupt memory for sequences. Vandierendonck, Kemps, Fastame and Szmalec (2004) also showed a detrimental effect of Random Interval Generation (RIG; participants are required to press a key at random intervals) on the Corsi Blocks Task and more recently Rudkin, Pearson and Logie (2007) showed an effect of RIG on memory for a sequential presentation of locations and no effect when locations were simultaneously presented.

The above evidence largely supports Logie's proposal of a visual cache responsible for representations of static visual information and inner scribe processes responsible for the maintenance of more dynamic spatial sequences and movements, with the latter perhaps being more intimately linked to executive processes (Logie, 2003).

1.3.2. Memory for Visual Matrix Patterns

The work of Phillips and colleagues (Avons and Phillips, 1987; Phillips, 1974; Phillips and Christie, 1977a; 1977b) is central to the present thesis and although much of the research was conducted during the earlier stages of the conceptualisation of working memory, it is nevertheless important with respect to the conceptualisation of both VSWM and the processes by which multiple representations in working memory may be combined.

One of the prominent methodologies employed to investigate visual memory involves the use of difficult-to-name visual patterns. Phillips (1974; Phillips and Christie, 1977a; 1977b) devised a paradigm involving memory for sequences of visual matrix patterns. Such patterns were white grids, with half of the cells filled in black at random. Participants are presented with a sequence of patterns and then recognition of the patterns is tested in reverse serial order (i.e. the final study pattern is the first test pattern). Using this procedure, Phillips and Christie (1977a; b) have shown a serial position curve for novel matrices, with a marked one-item recency effect, no primacy, and a flat function of above-chance recognition performance on all pre-recency items. The authors suggest that visual STM for novel stimuli is particularly vulnerable to the introduction of subsequent stimuli and perhaps may be limited to a single item. Phillips and Christie (1977b) demonstrated that the one item recency effect was unaffected by sequence length and visual masking but highly sensitive to the performance of mental arithmetic in the maintenance, implicating executive resources in the maintenance of the final item. Several authors have proposed that the matrix patterns used in such studies, although randomly generated, may contain familiar forms (e.g. Avons & Phillips, 1987; Broadbent & Broadbent, 1981), such categorical representation is proposed to be responsible for the above-chance recognition performance of the pre-recency items.

There is considerable evidence in support of distinct short- and long-term components in visual memory for patterns (e.g. Kroll, 1975; Phillips & Christie, 1977a; 1977b; Posner, Boies, Eichelman & Taylor, 1969). These components have been characterised as follows. Firstly, Avons and Phillips (1980) demonstrated that the short-term component increases as a function of display time much more rapidly than the long term component. This suggests that the encoding of the long term component is more time dependent. As discussed above, the short term component, seems to only hold a single item (e.g. Phillips, 1974; Phillips & Christie, 1977a; 1977b) and involve active maintenance as its decay function varies and the recency effect is removed by mental arithmetic (Phillips & Christie, 1977b). The same studies have shown that the long term component appears to persist despite the visualization of subsequent stimuli or performance of other intervening visual tasks.

Avons and Phillips (1987) measured the long term component in visual pattern recognition by using a secondary task that places heavy demands on visualisation. They then varied the change in semantic classification between the target and the distracter in a two-choice recognition paradigm. They found that when a secondary visualisation task was employed, performance was much more reliant on the difference in semantic classification between the target and distracter, suggesting that recognition of these patterns is more reliant on the semantic information. They also showed a slow increase in LTVM performance when display time increased, suggesting an increase in the amount of information being classified semantically. This supports the notion that the pre-recency items observed in serial position curves for matrix patterns are maintained in a categorical form.

The question that arises from the work of Phillips and colleagues that is of particular theoretical interest to the present thesis concerns the mechanism(s) or component(s) of visual working memory responsible for the one-item recency effect and above chance performance of pre-recency items, and the integration of the short- and long- term representations put forward by Phillips (1983). Several possible explanations of the observed results will now be considered.

1.3.3. Kosslyn's Computational Model

Kosslyn (1994; 2006) proposed a computational model of mental imagery (see figure 1.2.) and high-level visual perception. Simplified, it consists of several components which can each be divided into subcomponents, all of which work together to identify objects and their specific locations. The key component being the *Visual Buffer,* a system which maintains visual information and has a limited capacity leaving it susceptible to 'overflowing' by large images (Kosslyn, 1978). The Visual Buffer works with an *attention window* focussing on the section of the stimuli to be manipulated or inspected further (Egly, Driver & Rafal, 1994). Information from the attentional window is sent along at least two pathways, one concerned with object identity (Ventral pathway) and one concerned with location and spatial properties (Dorsal pathway). Spatial based (*Spatial Properties Processing Subsystem*) and object based (*Object Properties Processing Subsystem*) systems are presumed to analyse the spatial locations and physical properties of objects respectively. These subsystems feed object property and identity information along with configural and structural information of objects and scenes to an *associative memory* component. A short term associative memory stores information online pertaining to which objects are in which locations and links between representations from the subsystems. A long term associative memory has properties similar to the LTS. When the input into long-term associative memory does not sufficiently match a stored representation, familiar forms, closely matching representations and distinctive parts of the object are activated and passed to an *information shunting subsystem*. This subsystem passes information to *attention shifting* mechanisms which shifts the focus of attention to characteristic features of an object and can also shift the eyes, head and even body to aid recognition. The information shunting system also primes the object properties-processing subsystem to facilitate further processing of a particular part of characteristic. Unfamiliar objects or characteristics are then encoded into the visual buffer and passed through the system again. In comparison to Logie's (1995) model, Kosslyn's computational model provides an alternative account of these processes and specifies in more detail the nature of processes underlying VSWM.

One of the key structures in this model is the *visual buffer* which acts as a gateway through which visual input is passed on to other parts of the cognitive system, further to this it also receives input from these cognitive systems. Suggesting it is the primary focus of forming mental images of either memories of recently perceived information or images generated from prior knowledge. In this sense, the visual buffer is similar to the VSSP in Baddeley and Hitch's (1974) model, both receive input from perception or through direct retrieval from LTM.

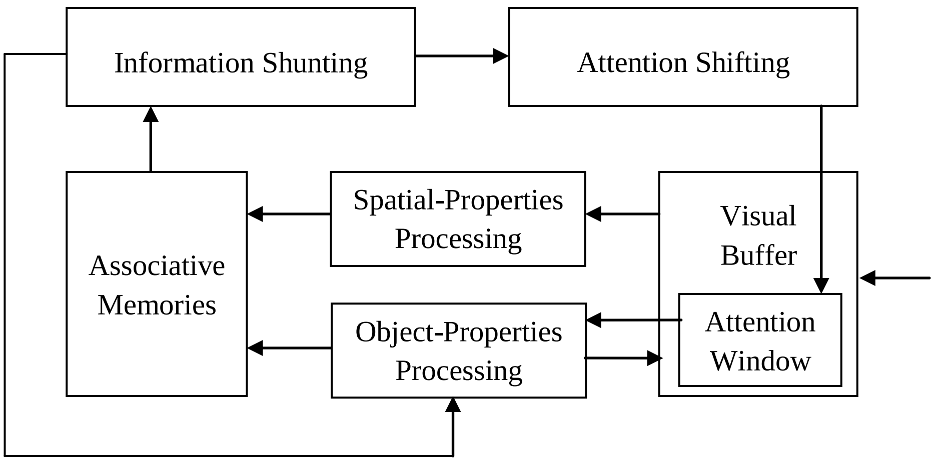


Figure 1.2. Kosslyn's computational model, taken from Kosslyn (2006, p 136)

Information which enters the visual buffer is passed on to a *object processing subsystem* which encodes stimulus characteristics and aids object recognition. An object is recognised when it then enters associative memory, if the perceptual input (or buffer output) matches long term representations. When information which enters associative memory only partially matches a stored visual representation it flows back to the visual buffer to supplement the representation. For example, the input from a complex object may only contain information from one viewpoint and may need to be rotated or inspected to allow for a greater match with a stored representation. When the information is sent back into the visual buffer for additional processing, the attentional window can select parts of the input for inspection. Pearson (2001) proposes that the one item recency effect seen in Phillips and Christie (1977a; 1977b) could be due to the final image in the sequence being consciously imaged in the visual buffer, with all other items being stored offline in associative memory which is proposed to store information from both the dorsal and ventral streams along with semantic and verbal information (Kosslyn & Shin, 1994). However, Logie and Van der Meulen (2008) suggests that the novel visual matrices used in such studies would not readily lend themselves to being represented in a system such as associative memory as the possibility for full semantic representation is greatly compromised. This will be investigated and discussed further in Chapters 7 and 8.

1.3.4. Pearson and the Visual Cache-Visual Buffer Model

Logie and van der Meulen (2008) propose that the visual cache in Logie's (1995; 2003) model of VSWM is functionally distinct from a system responsible for conscious visual imagery, such as Kosslyn's visual buffer. Based on a combination of Kosslyn's (1994) model and Logie's (1995) model of VSWM, Pearson (2001) went on to develop a model of VSWM (see figure 1.3). This model further fractionates VSWM into three slave components and the central executive. The first of the slave systems is the *Visual Buffer*. Very similar in nature to Kosslyn's visual buffer; it is responsible for consciously maintaining a visual representation. Such representations can come directly from long-term visual memory (LTVM) or can be generated by the Central Executive and the Inner Scribe. Representations stored in the buffer decay very rapidly but can be regenerated by the central executive. The Visual Buffer is assumed to have a limited capacity, in that it is not capable of representing a series of visual representations. In fact, it is proposed that a person can only experience one mental image at a time, with the exception that multiple representations can be integrated to form one. However, when novel and abstract images are presented this may prove to be very difficult and as such successful visualisation would only be possible for the final item as seen in the work of Phillips and Christie with all pre-recency patterns in the sequence being attributed to associative memory in Kosslyn's model (discussed above). This visualisation strategy has been demonstrated in other serial order tasks such as static visual images representing the spatial sequences in the Brooks Matrix Task (Smyth & Pendleton, 1989) and the Corsi Blocks Task (Kemps, 2001), evidence has also been provided suggesting participants use a visual representation in backwards verbal recall (Li & Lewandowski, 1995).

The second component is the *Visual Cache*. This provides support for the visual buffer and serves as a temporary backup store for representations which are no longer in the form of conscious mental images. The cache is not proposed to be used in high level object recognition (Pearson, 2006). Thus the pre-recency matrix items in Phillips and Christie's studies would be stored offline in the visual cache, while the final item is maintained and imaged in the buffer. The final component of the Pearson model is the *Inner Scribe* which is involved in the encoding of spatial locations and the short-term store of spatial sequences. This can be carried out independently of the cache and buffer; however the buffer can be involved during the retention of spatial sequences if the participant consciously images the sequence. The scribe does not have any connection with the maintenance of images in the buffer or the maintenance of visual material in the cache. It is suggested that the central executive helps rehearse information in the buffer, in a similar way to the 'attentional window' in Kosslyn's model but that information in the visual cache is not demanding of these processes.

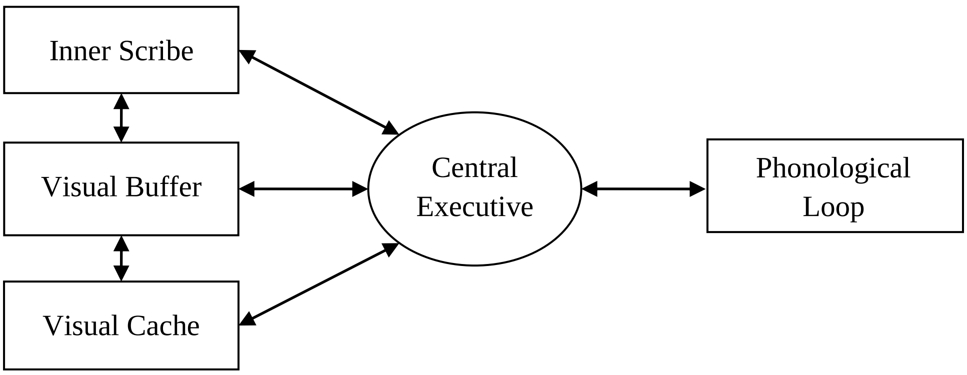


Figure 1.3. Pearson's (2001) Visual Cache- Visual Buffer model of working memory

In this model, it is proposed that the one-item recency effect is a function of that item being consciously represented in the visual buffer and all other items being temporarily stored in the offline visual cache. This would explain why the executive interference in Phillips and Christie (1977b) had its greatest effect on the recency item as it is proposed that the cache does not demand executive resources. Logie (2003) maintains that information within working memory has not come directly from perception, as such it is already interpreted to some extent, and proposes that information such as novel matrix patterns may be stored in the visual cache, this issue will be developed further in chapter 4.

1.3.5. Baddeley and the Episodic Buffer

As discussed above, Baddeley (1986) abandoned the notion of a central executive with its own storage function by adopting a model of control similar to that proposed by Norman and Shallice (1986), where the central control system is not responsible for storage. Taking away the storage function of the central executive leads to two major criticisms. Firstly, given the mutually exclusive codes used by the two slave systems, it becomes unclear how information from both systems could be combined into a coherent representation of a single stimulus or event.

Secondly, as discussed above, in Logie's (1995) revision of the WM model input occurs via activated LTM rather than via the perceptual system, making working memory a workspace for activated LTM rather than a gateway leading from perception to LTM. This revision takes into account and places greater emphasis on the contribution of long term knowledge to working memory storage and processing as suggested by numerous studies (Baddeley, 1996; 2000; 2002; Baddeley & Logie, 1999; Logie 1995). This also revises the assumption of a unidirectional exchange of information between the two systems. Baddeley (1996) proposed that activation of LTM is a function of the central executive, however the central executive is thought to have no storage capacity of its own, as such no means of maintaining representations activated in LTM.

In response to these criticisms, Baddeley (2000) proposed a further component in WM, *The Episodic Buffer* (See Figure 1.4). Repovs and Baddeley (2006) specify that the term 'episodic' indicates the involvement of complex structures or episodes. While 'buffer' specifies that it interfaces with other perceptual and mnemonic systems. It is proposed to be a temporary storage system which functions as an interface between different sources of information such as perceptual (e.g. visual, auditory, and tactile) and mnemonic (e.g. episodic, semantic) sources, each of which may contain different codes (e.g. visual, phonological, semantic etc). Control of the Episodic Buffer is attributed to the Central Executive which retrieves information from it in the form of conscious awareness and may also attend to a source of information and therefore actually influences the contents of the buffer itself. Rehearsal within the buffer is similar to continued attention to the representation (Baddeley, 2007). A central feature of the episodic buffer is its role in binding information from different sources into 'chunks', although chunk capacity is presumed to be limited (e.g. Cowan, 2000; Tulving & Patkau, 1962), capacity can be increased by binding additional information into each chunk (Miller, 1956). The process of binding may be attentionally demanding in comparison to retrieval from LTM.

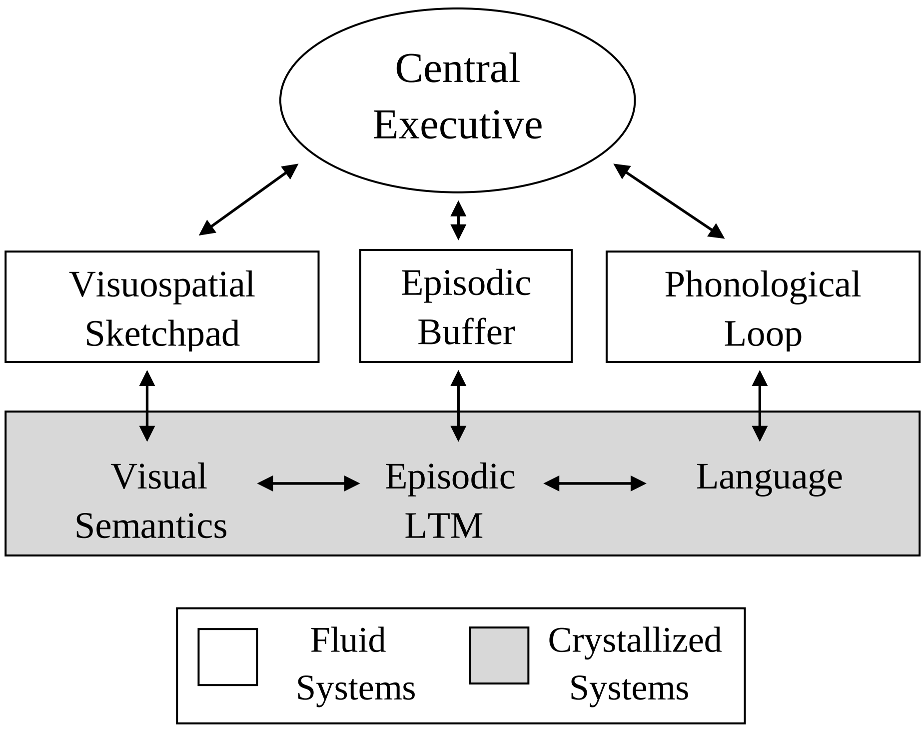


Figure 1.4. Baddeley's (2000) conceptualisation of working memory

Support for the episodic buffer comes from a number of sources. Logie, Della Sala, Winn and Baddeley (2000) presented participants with words in a visual format which were both visually and phonologically similar (e.g. hew, dew, cry, dry) and words that were visually distinct yet phonologically similar (e.g. guy, sigh, blue, ewe). The latter produced improved recall, and this effect was present even without articulatory suppression. The authors propose that the verbal sequences presented in a visual modality are either stored in both visual and phonological codes which are bound together into 'episodes' or perhaps stored in a multidimensional code in the Episodic Buffer.

Baddeley and Wilson (2002) reported the cases of two amnesic patients who demonstrated deficits in LTM function but preserved prose recall. Prose recall requires the binding of semantic lexical information with working memory representations. The patients demonstrated normal immediate recall for prose but compromised performance following a delay. The authors also point out that the number of words in the prose passage far exceeded the capacity of the phonological loop and as such must be dependent on chunking of information. This chunking is dependent on the processing of the words based on semantic processing and as such must be taking place in working memory, this cannot be accommodated in the tripartite multi-component model.

Bor and Owen (2007) manipulated different methods of strategic coding in a working memory task. This coding could be based on mathematical redundancy (e.g. numeric regularity) or pre-established mnemonic sequences (e.g. sequences participants are required to memorize prior to the task). Both of the strategies improved performance relative to when no coding strategies were available, suggesting scaffolding of performance by LTM (one of the presumed functions of the episodic buffer). Using fMRI they showed that activation of the prefrontal-parietal network was increased in the LTM conditions relative to the control conditions (no coding strategies). The authors propose that this indicates the functioning of the Episodic Buffer.

The introduction of the Episodic Buffer replaces the function of combining LTM and WM information that was originally assigned to the central executive. This would suggest that there is a strong relationship between central executive processes and the episodic buffer, and that the two are related in a way that the use of the episodic buffer will engage executive resources (Baddeley, 2000). The amnesic patients described by Baddeley and Wilson (2002), and discussed above, showed preserved binding function. These patients were also shown to have relatively intact executive function, supporting the notion of an intimate link between the two processes.

The role of the executive in the binding of information has been investigated in two broad fields. Firstly, one concerning prose recall and the other concerning the binding of low level visual features of an object. Both of these bodies of work will be discussed at length in chapter 3.

With regards to the present thesis, a point of interest is how the updated model of working memory can accommodate the dual representation of visual matrix patterns observed by Phillips and Christie (1977a; 1977b). It would seem logical that the one item recency effect would be attributable to the visual representation of the patterns being held or visualised in the VSSP and refreshed via executive resources, with pre-recency items being stored in a categorical form within the Episodic Buffer.

1.4. Dual Representation in Visual Working Memory

Awh, Barton and Vogel (2007) demonstrated that performance in visual working memory can be increased by improving the quality or fidelity of information stored, which would in turn allow for greater descriminability at test. They suggest further that categorical storage and the fidelity of representations reflect distinct abilities with a possibility of dual representation of the two formats. An argument supported by neurophysiological evidence (Agam et al. 2009; Serences, Ester, Vogel & Awh, 2009; Xu & Chun, 2005). To allow for this, the architecture of WM must be able to accommodate the simultaneous presence of dual representations. This is an issue which Pearson (2001) identified when aiming to account for the pre-recency visual matrices in work of Phillips and colleagues discussed above. This work showed a clear one-item recency effect for the final pattern in a series of matrices; however, earlier items in the sequence were also recalled above chance level. It is evidence such as this that lead Pearson (2001, discussed above) to argue for the requirement of two WM processes in tasks such as the matrices where dual representations are present; a process which maintains the last item in relatively fine pre-categorical detail and a process which may maintain the pre-recency items in categorical form. In the Logie (1995; Logie & van der Meulen, 2008) conceptualization of VSWM, only one process is associated with visual memory representation, the visual cache, which doesn't lend itself readily to dual-representation. In the Baddeley (2000) model the VSSP process is identified for visual processing. Baddeley introduced the *Episodic Buffer* process into his model, a process capable of the binding and integrating multiple formats, it is thus possible that the categorical representation could be maintained within the Episodic Buffer. Indeed given the dual representations, some form of binding process of low level representation and semantic categorical representation may be required for the participant to maintain a stable representation in the face of the fragility of working memory episodic bindings (Allen, Baddeley & Hitch, 2006: Logie, Brockmole, & Vandenbroucke, 2009). The concept of binding will be examined again in Chapter 3.

1.5. Chapter Summary

This chapter has traced the development of multi component models of working memory from its initial conceptualisation in 1974 through to contemporary models. A focus has been placed on the possibility of dual representations in visuo-spatial working memory and how this is not readily accounted for in many early models. Three modified accounts of working memory have been discussed, each which considers the importance of LTM and executive resources in visual working memory task performance. The ability of these models to accommodate research regarding visual matrix patterns was considered. The following chapter will focus on models of working memory that have developed in parallel to the ones presented here, that predominantly view working memory as activated long-term memory.

CHAPTER 2

Working Memory as Activated Long Term Memory

2.1. Chapter Overview

In contrast to the models of working memory presented in chapter 1 a differing theoretical approach has developed in parallel. In such models working memory is defined by the processes involved in the performance of complex cognitive activities with a focus on executive control and integration with LTM. The previous chapter provided description of how multi-component models of Visual Working memory can account for dual-representations. Findings in favour of regarding the Episodic Buffer as a separate component of working memory within the framework of the multi-component model (Baddeley, 2000) can also be understood in terms of other models of WM that emphasise the importance of the link between working memory and LTM. The present chapter will provide an outline of Cowan's (1988; 1995; 1999; 2005) model of working memory, which views working memory as the temporary activation of LTM representations and a limited capacity focus of attention. It will also address how such a model is able to account for dual-representation, again with a focus on visual working memory research.

2.2. Contrasts with Multi-Resource Models

Modality Specific Stores. The multi-component models of working memory discussed in chapter 1 typically place great emphasis on the separation between verbal and visuo-spatial processes and also (perhaps more controversially) between visual and spatial processes. Cowan (2005) agrees that there is evidence of a dissociation between these processes but that there are distinctions between other modalities (such as verbal versus tactile) which are equally important but that models such as the Baddeley and Hitch (1974; Baddeley, 1986) model do not address. Cowan attempted to counter this problem by creating a general model of working memory in which the divisions between components correspond only to the most important distinctions between the processing capabilities of working memory. This model proposes that interference within modalities occurs not because of information competing in separable buffers but that interference simply occurs most between stimuli with similar features, i.e. Interference with visual information by an intervening visual task (e.g. Logie & Marchetti, 1991).

Short and Long Term storage. In the previous chapter is was suggested that information within STM is already interpreted to some extent, models such as that put forward by Logie (1995,2003) suggest that this is because information entering working memory passes through LTM. An alternative account of this phenomenon is provided by Cowan (1988) in which short term or working memory can be seen as items in LTM that are currently in a heightened state of activation. In the models discussed in chapter 1, short-term or working memory is seen as separable from LTM and there is evidence that differentiates the two stores in terms of capacity (e.g. Miller, 1956; Watkins, 1974), control processes (e.g. Conrad & Hull, 1964; Sachs, 1967) and duration (e.g. Baddeley et al, 1975). Cowan (1988) proposes that the properties of the two systems that have been observed are in fact due to differences in the processes involved . Specifically, retrieval processes involved in LTM tasks and the processes for maintaining activation in STM tasks.

Sensory Storage. A further distinction that is drawn is that between STM and sensory processes, Cowan (1988) proposes there are two types of sensory storage, the initial stage lasting only around 250msec and having potentially no limit on capacity (Sperling, 1960) and then a second stage, lasting potentially as long at short-term storage (Balota & Engle, 1981), in which information is partly interpreted (Cowan & Morse, 1986). This latter stage of sensory processing is proposed to be part of short-term storage (Cowan, 1988) and is of particular interest to the present thesis and as such will be discussed in greater detail in chapter 9. This distinction was observed in the work of Phillips (1974), who used a change-detection technique with matrix patterns. Phillips observed perfect performance in the maintenance of matrix patterns with a maintenance interval of 20msec, with performance gradually declining across maintenance intervals (the maximum interval measured was 9000msec). Phillips also noted that retention over short intervals (i.e. less than 300msec) was not affected by the complexity of the matrices, but that complexity had a significant impact at the longer durations. Finally, Phillips also noted that at intervals less than 300msec, offsetting the test matrix relative to the study matrix resulted in dramatic drop in performance; this effect was not present at longer maintenance intervals. Cowan (1988) takes this as support for an early sensory representation lasting up to 300msec which is unaffected by information load but greatly affected by offsetting the stimulus, and a later sensory process (> 300msec) or short term memory process which is limited in its capacity but insensitive to offsetting of the stimulus.

2.3. Cowan's Embedded Processes Model

In 1988 Cowan proposed an embedded processes model of working memory (named such by Cowan, 1999; See Figure 2.1), consisting of LTM, within which there is a subset of memory which is temporarily activated. Within this activated subset of memory is a smaller subset of information which is in the current focus of attention. It is assumed that information cannot be attended to without being activated and as such the focus of attention is always represented as being within the activated portion. However, it is also suggested that it is possible to have activated memory which is not in the current focus of attention; this concept is supported by several studies (e.g. Balota, 1983; Wood and Cowan, 1995). Information which is in the focus of attention can be linked to other pieces of information also in the focus of attention, leading to combinations of information within LTM. This process of 'linking' together representations is a function that is presumed to be carried out by the Episodic Buffer in the Baddeley (2000) model and is often referred to as *binding.* This will be discussed at length in chapter 3.

Cowan's model places great emphasis on the distinction between information in the focus of attention and information which is activated. The allocation of attention is proposed to be controlled by two processes; firstly the automatic recruitment of attention to salient events and changes in the environment and secondly, attention can be allocated voluntarily and effortfully via the Central Executive (Cowan, 1988). Activation of semantic information is more likely to be achieved via the latter (Conway, Cowan & Bunting, 2001). The embedded processes model also suggests that it is possible to direct attention away from elements of memory (inhibition); Engle, Conway, Tuholski and Shisler (1995) showed that inhibition and attention employ the same resources within working memory. The efficacy of retrieval in working memory is dependent on the level of activation and attention. Items in the current focus of attention are most readily available, followed by unattended yet activated information and finally the relevant information in LTM is also considered to be part of working memory as it can be accessed if necessary.

The figure presented below (figure 2.1) depicts working memory as a time-line beginning at stimulus offset. When a participant is presented with a stimulus it enters the sensory store which preserves the physical properties of the stimulus and can hold a representation for around 250 milliseconds (Philips, 1974). Concurrently, relevant representations within LTM are activated. Combined, this leads to the stimulus becoming coded and interpreted to some extent, storage of the activated features in STM and further codes being activated within LTM. A person can habituate to an activated code, this activated information will remain in STM but outside of the focus of attention. If a stimulus differs from the current activation (it is proposed that this occurs when there is a discrepancy between the current neural representation and new input, Sokolov, 1963) it may enter the focus of attention via the Central Executive which can direct attention and also activate information within LTM.

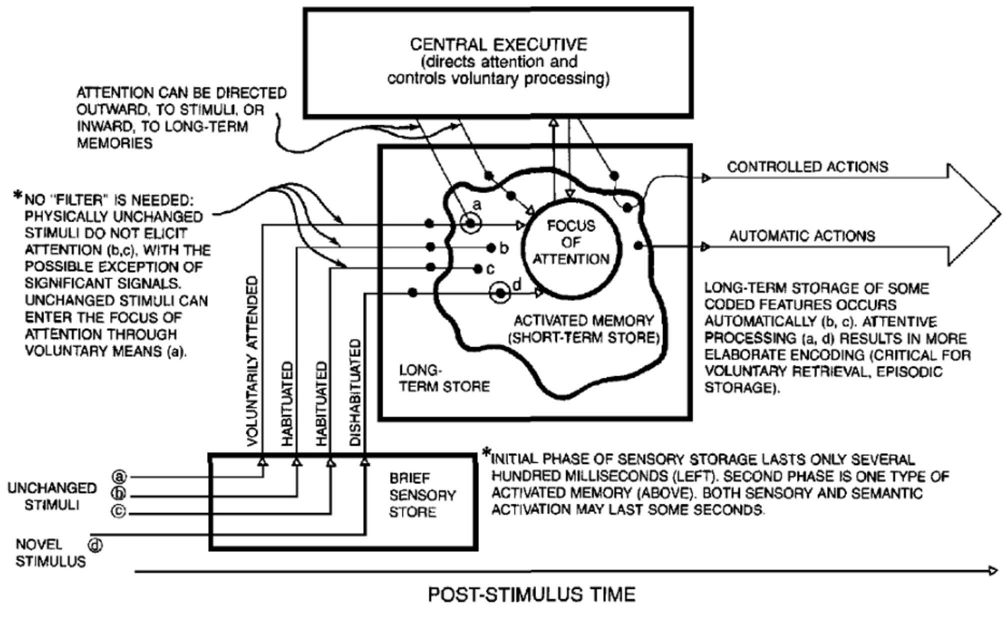


Figure 2.1. Graphical representation of the embedded processes model, taken from Cowan (1988), in which the processes in working memory are presented in a post-stimulus time line.

2.3.1. Processes within the Embedded Processes Model

Encoding. The activation of features by a stimulus forms the encoding of it in working memory. When the item is not attended to the activation is only partial and physical features are more likely than semantic features to be represented (Conway, Cowan & Bunting, 2001). When the stimulus is attended to, more of the features associated with the stimulus in LTM are activated and as such a more stable memory representation is formed.

Cowan, Lichty and Grove (1990) examined memory for consonant-vowel syllables that were to-be-ignored while a participant was reading a novel. When signalled, the participant had to recall the last syllable and summarise what was happening in the book. Consonant recall became worse with increasing retention interval, but vowels remained the same. This difference didn't exist, however, when the syllables were vowel-consonants, suggesting that speech information was activated automatically but that the more complex consonant information did not last as long in memory as the acoustically simpler vowel information. In another experiment of the same study, participants had to divide their attention between reading and listening and press a button when a particular sound was heard. The difference between consonants and vowels no longer existed and performance didn't decline across retention intervals. The authors interpret this as evidence for enhanced encoding through the production of longer-lasting categorical representations instead of acoustic ones. Cowan et al (1990), in a further experiment, got participants to whisper the book they were reading to examine any breaks in reading that could indicate a shift of attention towards the syllables. On the trials in which participants did break in reading (17% overall) the consonant-vowel difference was much smaller, providing support for the idea that shifting attention towards the stimulus can create a longer-lasting memory representation.

Representation and Maintenance. As discussed in the previous chapter, there is evidence that verbal short-term retention is impeded by competing verbal activity (articulatory suppression) whereas visuo-spatial short-term representations are impaired by competing visuo-spatial activity (Baddeley et al, 1975; Vogel, Woodman & Luck, 2001). This leads to the conclusion that representations in memory are interfered with by similar representations (e.g. Della Sala et al, 1999).

Cowan (1988) however, pointed out that there is the possibility of more types of storage than just verbal and visuo-spatial and that a possible point of interest could be the similarities between the properties of different types of storage. He points out that in each modality the ability to detect changes between two stimuli declines across retention intervals between 10s and 20s, that interference is greatest from similar stimuli in the same modality and that the same is true for internal codes or representations. Therefore similar properties appear to characterise various types of temporary activated memory. Thus, Baddeley's Phonological Loop and Visuo-Spatial Sketchpad discussed in the previous chapter are proposed to be simply two types of memory activation and the processes used to reactivate the memory (See Glenberg, 1997 for a similar argument)

In the embedded processes model of working memory, maintenance is achieved by keeping the to-be-remembered material in the focus of attention. Further to this Cowan (1992) proposed that the process of searching through a set of items can help to reactivate them and these items may be re-circulated through the focus of attention. Cowan (1992) studied children and found that as to-be-remembered word list length increased the duration of the gaps between words in the child's response also increased significantly. Closer inspection showed that those who recalled more items did so in a response that lasted longer, suggesting that the processing that occurs during recall may have served to reactivate the memories between responses, resulting in a longer response time. Cowan (1999) proposes that this doesn't occur by verbal rehearsal but perhaps by a mental search for the correct item to recall next, thus allowing for the item to enter the focus of attention and be reactivated briefly. The competition between processing and storage is discussed in more detail below and will be examined in closer detail in chapter 8.

Retrieval. In this model retrieval is achieved by the correct items entering the focus of attention. Long term representations have a much richer information structure than short term and as such retrieval from it is only time limited for practical reasons such as the amount of time allowed for recall. Retrieval from activated memory must occur within a limited amount of time as the activation of items fades and there is the possibility for interference to occur among concurrently activated items. Baddeley (1986) proposed that a person can recall as much from a stimulus as they can pronounce in 2seconds and that this speed is representative of covert rehearsal. Cowan et al. (1994) found that in children word length altered the duration of words in spoken responses but not the time in between responses (representative of covert rehearsal). Further to this, they report that the age of the child altered the inter-word gap but not the duration of the spoken words. They propose that age may improve span by increasing the speed of covert rehearsal during recall and the word length effect may influence span by altering the rate of overt pronunciation in recall. This has obvious implication for maintenance. As the speed of covert rehearsal in children increases, it would be expected that the amount which can be maintained and rehearsed would also increase.

Control of Working Memory. In this model the central executive is responsible for all information processing that is under voluntary control. Cowan (1988) presumes there is a limited capacity to the amount of processing that can be carried out and that a person is aware of all information processed by the executive. Voluntary memory activation is presumed to be achieved by the CE (Cowan, 1988) and is also proposed to involve the inhibition of non activated categories of information. Schvaneveldt, Durso, and Mukherji (1982) suggest that information may be activated automatically by changes in the environment and recruit the involvement of the CE to redirect the focus of attention allowing for greater activation where necessary. The involvement of executive processes in retrieval from LTM is proposed to be greater when the items were stored via effortful or voluntary processes.

An integral part of the embedded processes model is that it proposes dual control of attention in working memory. As discussed above, control can be achieved by the Central Executive but also changes in the environment appear to recruit attention. Voluntary regulation of working memory is attributed to the Central Executive's ability to control the focus of attention. Items in the focus become activated, but as discussed above the amount of information that can be activated is greater than the amount that would fit in the focus of attention.

Broadbent (1958) showed it is easier to attend to one of several channels if they are distinguished by physical characteristics rather than just semantics. However, Moray (1959) demonstrated that in such circumstances some semantic information is encoded as well. Cowan (1988) proposes that all stimuli activate some elements in memory but that this activation is enhanced for attended stimuli. If a participant wants to ignore a repeated stimulus they can but some features will still be activated in memory and compared to existing neural models, as discussed above most semantic features aren't processed automatically in unattended stimuli and as such will not be compared to existing neural models. A participant can also choose to attend to a repeated stimulus; this is done via the central executive under voluntary control (Waters, McDonald & Koresko, 1977). The orienting mechanism and its habituation allow processing of unattended information to take place, the central executive uses effortful processes to help direct the control of attention, both of these processes operate together.

2.3.2. Working Memory Limitations

The development of this model is strongly linked to research on the capacity of working memory. As such a discussion of how Cowan's model views the limits of working memory is extremely pertinent. Cowan (1995) proposes that capacity is primarily a limit of the focus of attention and time limits are primarily associated with activated memory.

Capacity Limitations. It is presumed that there are capacity limits to activated memory; Cantor and Engle (1989) propose that participants with low working memory span have less activation than high span participants and as such their activation must be spread thinner when it must be shared among more than one item. However, Conway and Engle (1994) demonstrated that changes in response time as a function of set size only affect working memory span if each target item was used in sets of more than one where participants had to suppress non-target occurrence of the item. They then reinterpreted the findings of Cantor and Engle as the ability of high span participants to inhibit irrelevant information on a particular trial (This has subsequently been supported by ERP work of Vogel, 2008). The limit to the number of items that can be in the focus of attention is perhaps simpler, it may be that a person can only focus on one general group of related items at any moment and not many unrelated items or schemes (Cowan, 1999). This notion is similar to the one-item capacity proposed for the visual buffer in both Pearson's (2001) and Kosslyn's (2006) model. Research into dichotic listening supports this, it appears that a person cannot comprehend the meanings of two people's speech when one is presented into each ear (e.g. Broadbent, 1958). Cowan (1995, 2000) proposes that the capacity of the focus of attention is about 3 or 4 chunks (see Cowan, 2005, for a full review of capacity limits)

Time Limitations. Many studies have shown memory for verbal and acoustic information decays across 10 to 30 seconds (see Cowan, 1995, for a review). Peterson and Peterson (1959) demonstrated a decline in the retention of trigrams during a distracting task over 18 seconds but Keppel and Underwood (1962) showed that this didn't occur on the first few trials suggesting the effect observed was actually an effect of proactive interference. Cowan (1988) suggests that even when decay has taken place the last trigram could still be retrieved on the basis of the LTM representation unless the proactive interference is sufficient to prevent long term retrieval. Cowan (1999) stresses that the amount of time necessary for memory decay is relative and not absolute, and evidence for this comes from research into the long-term recency effect. Standard recency is eliminated when a distracting period is placed immediately after the list to be recalled, however, if a distraction period is also put in between each item (continuous distraction procedure) the recency effect is observed despite the distracter period after the final item being great enough to eliminate the effect. Cowan interprets this as meaning that larger ratios between the inter-presentation interval and the retention interval (i.e. a distraction period equal to the inter-presentation period) result in greater performance (for a review of this evidence see Cowan, 1995; and Baddeley, 2007). As well as the recency effect, the word length effect has also been studied in this way; Cowan, Wood and Borne (1994) showed that there was an advantage in immediate recall for lists in which the words recalled early on were short rather than long. However, with the continuous distracter procedure there is actually an advantage for long words, perhaps attributable to the greater number of phonological cues in LTM. The idea of time limited activation is necessary because without it, what is seen as activated STM would just be a part of LTM representations that are relevant to the situation with no limits on what this could include. In contrast, the only discussion of a time limit of the focus of attention is by Cowan (1999) who describes work on vigilance, which suggests that attention cannot be sustained indefinitely because of a limit to a person's state of awareness.

The notion of there being no time limit to information held in the focus of attention is critical to the thesis and will be discussed in chapter 9.

2.3.3. Resource Sharing in Working Memory

Some of the research discussed above, makes explicit the importance of the ability to alternate between storage and processing in working memory. The nature of the focus of attention described thus far creates the opportunity for competition between processing and storage of information. As such, this is an important notion for the present model. In terms of the present thesis; resource sharing is discussed further in chapters 4, 7 and 8. Morey and Cowan (2005) attempted to investigate the competition between storage and processing in working memory tasks, they used the visual change-detection procedure used by Luck and Vogel (1997, discussed in greater detail in chapter 3) embedded within one of four verbal memory tasks. Participants were required to repeat either 2 or 7 digits at a rate of 3/second or their own seven digit phone number and in a final condition there was no verbal memory load. The visual array task consisted of two arrays of coloured squares (of either four, six or eight squares) being presented in succession. The second was either the same or differed by one square, and in this array one of the squares was circled to indicate that this is the square that may or may not have changed. The verbal task continued until participants had made a same/different response. The phone number condition was seen as a control for the seven-digit load condition, as the two tasks place equivalent demands on articulatory resources but the phone number condition didn’t have the same mnemonic load as it was a familiar digit sequence. They found no interference effects of the 2 digit and no load conditions but highly significant interference effects of the 7 digit load. Importantly the phone number condition showed interference equivalent to the 2 digit condition. They propose that this serves as evidence that the interference occurring is not due to the load the 7 digit condition places on phonological processes. They went on to show that the impact of the seven digit load was much greater on the trials where the digits weren’t correctly recalled, they propose that this is due to the additional attentional demands of difficult digit sequences. Where simple ones can be maintained in the phonological loop without much need for attentional resources, this is less simple for complex digit sequences. Suggesting that the storage of the visual information is compromised by the processing of the digit sequences which demand attentional resources.

Cowan (2005) points out that the central executive involvement in the above study could be due to the demands of encoding or retrieval and not necessarily storage but puts forward evidence against this. Morey and Cowan (2005) suggest that the first few rehearsals of a digit sequence are the most demanding, they asked participants to begin articulation either before or after presentation of the first visual array and found interference to be greater when articulation began at the onset of the retention interval suggesting it is having its effect on storage not encoding. Furthermore, Woodman and Vogel (2005) propose that consolidation of the visual array is achieved in roughly 50msec per item to be encoded and as such would have occurred prior to the onset of articulation. The time needed for consolidation of material in visual working memory may be dependent on the complexity of the items to be-remembered; the time course of this encoding process will be investigated and discussed in chapter 6.

From the above studies, it is unclear whether the executive involvement seen is due to direct recruitment of attentional resources in the storage and processing of information (Cowan, 2001) or indirect recruitment, for example, executive resources may be recruited for rehearsal in the aid of storage (Baddeley, 1986; Hester & Garavan, 2005).

Cohen (2005) proposes that the work of Daneman and Carpenter (1980), which will be discussed in more detail below, can be taken as support for the focus of attention being involved in both processing and storage. Daneman and Carpenter devised the *sentence span task*, in which participants must process a sentence and make a judgement based on it, while maintaining the last word of the sentence. For example participants may be presented with the sentence *"Cows are living animals"* to which they would response "true" and need to remember the word "animals". They are presented with an increasing number of sentences until they reach the maximum number of words that they can reliably recall while still being able to correctly comprehend the sentences. This is taken as that person's individual capacity and is normally between 2 and 6 items. Many complex span tasks have been produced based on this protocol, all of which rely on the recruitment of both processing and storage (e.g. *Operation Span*; Turner & Engle, 1989; *Counting Span*; Case, Kurland & Goldberg, 1982). Case et al (1982) devised a counting span task, in which participants are required to count the number of items in an array and remember the totals; they showed that more demanding counting results in poorer recall and therefore lower span. Case (1985) went on to propose a *cognitive load hypothesis* in which both processing and storage share a common limited pool of resources and the difficulty of the processing task leads to a trade-off between processing and storage. In contrast to this Towse and Hitch (1995) propose a *memory decay hypothesis* in which memory traces of to-be-remembered items suffer time-related decay while the concurrent task is being performed. Towse, Hitch and Hutton (1998) propose that in complex span, more difficult concurrent tasks involve longer durations of processing and therefore result in more decay. Some resolution of this debate can be gained through the work of Barrouillet and colleagues discussed below.

Barrouillet and Camos (2001) manipulated the processing load of the concurrent task in a complex span procedure while keeping the duration of the load constant, this was achieved in a task they referred to as the *baba span task* in which the concurrent task is simply repeating the word *ba* for a particular length of time, which controls for both the duration and the effects of articulatory suppression in counting and operation span. In 6 – 11 year olds they found no difference between baba and counting span supporting a memory decay hypothesis; however they also found that operation span was lower than baba span, supporting a cognitive load hypothesis. A series of studies followed to resolve this debate.

Barrouillet, Bernardin & Camos (2004) looked at recall of consonants while participants either repeated a meaningless syllable or read digits out loud. In the latter condition participants were presented with consonants with a gap of either six, eight or ten seconds in between and were required to read four, eight or ten digits in this period. Performance dropped linearly as a function of the number of digits to be read aloud in the interval. This was taken as being indicative of attention being switched away more frequently from the reactivation of the consonants to be recalled when reading allowed an increased number of digits (Cowan et al. 1999). Lepine, Bernardin, Barrouillet (2005) devised a *continuous operation span* task in which the concurrent task is a computer paced simple processing task (adding and subtracting 1 to a small number), proposing that a simple task that requires continuous processing and as such prevents switching would be highly detrimental to span. They varied the pace of the operands and confirmed that the effect of concurrent activity on span is dependent on the extent to which it captures attention with a fast enough rate leading to performance equivalent to that of traditional operation span. In a further experiment they eliminated the possibility of this being due to the effects of articulatory suppression by requiring a key-press response and replicating the same effects.

Based on the results presented above, Barrouillet and colleagues have proposed a Time-Based Resource-Sharing hypothesis (TBRS) in which both processing and storage require attention and that memory traces of to-be-remembered information decay as soon as attention is switched away in aid of processing.

2.4. Dual-Representation in Activated LTM Models

In the above sections the basic mechanisms of Cowan's embedded processes model have been outlined. Of interest to this thesis is how this model can explain the phenomena of interest in the previous chapter. Namely those observed by Phillips and colleagues in which single item recency effect is observed in a serial order visual matrix pattern task, while above chance performance on pre-recency items is maintained.

In Cowan's model conscious imaging of a single item, would appear to be attributed to the focus of attention. As discussed above, the focus of attention is proposed to be of limited capacity and as such this could be the component responsible for the one-item recency effect. The pre-recency items that are recalled at a lower level (but still above chance) would be assigned to the short term store, proposed to hold items that are activated yet not in the current focus of attention. Cowan (1988) proposes that such items would rely more heavily on their categorical or semantic features; this would be consistent with Phillips and Christie's (1977a; 1977b) original proposal that the task represented a short- and long-term visual memory. Cowan accepts in this model that both sensory and semantic representations in the short term store may remain activated for some seconds (Cowan, 1988), allowing for the maintenance of novel matrices which do not map very well onto existing representations outside of the focus of attention.

This may relate to the later sensory processing discussed above, Phillips (1974) found that at maintenance intervals greater than 250msec memory for matrices became insensitive to visual masking and offsetting of the study and test stimuli. Cowan (1988) proposes that this represents a shift from early sensory processing to a later process in which the information available is partially interpreted and represented in short term memory as sensory information combined with activated LTM representations.

The nature of the focus of attention would allow for an effortful and gradual build up of semantic representation for items contained within it (Conway, Cowan and Bunting, 2001), as such categorical and sensory features would be activated and remain activated when the successive items are presented and the item leaves the focus of attention. Fine perceptual features of the objects would degrade at this point, hence the strong recency effect for the final item, which doesn't leave the focus of attention. The TBRS model briefly introduced in section 2.2.4 would allow for the representations of past items to be activated by brief switching across successive presentations and by visual search through the items in activated memory at recall.

2.5. Chapter Summary

The present chapter began by discussion differences between the multi-component models discussed in chapter 1 and unitary models of working memory. In contrast to Baddeley's model of working memory, Cowan's model does not draw such a clear distinction between verbal and visuospatial processes, but rather specifies that different codes may be processed by the same mechanisms and that more than these two types of codes may be equally important in working memory. However, since the addition of the Episodic Buffer to the Baddeley model in 2000, more similarities between the two theoretical approaches have become apparent. These similarities will be discussed in the following chapter.

The mechanism(s) by which dual-representations of a stimulus may be formed and held within working memory, in particular visual working memory, is a central concept in this thesis. The extent to which multi-component models accommodate multiple representations of novel matrices was discussed in the previous chapter. The extent to which Cowan's model can accommodate the same phenomenon was discussed in section 2.3 of the present chapter. The following chapter will deal with how the integration (or binding) of multiple representations of a stimulus in working memory may be achieved according to both multi component models (discussed in chapter 1) and activated memory models (discussed in the present chapter).

CHAPTER 3

Integration of Representations in Visual Working Memory

3.1. Chapter Overview

As demonstrated across the previous chapters, two differing theoretical perspectives have developed in parallel which both attempt to characterise working memory processes. However, since the addition of the Episodic Buffer to the multi-component model by Baddeley (2000), the predictions made by the two models have become increasingly similar. The present chapter will initially outline some important similarities between the models, namely the increasing research interest in the integration of the components or processes of working memory. Two bodies of research into binding of multiple representations will be discussed, firstly one considering the nature of the binding together of low-level visual features and secondly one which considers the integration of phonological and long-term semantic information. The final point of the present chapter will be to consider how research employing visual patterns could contribute to this body of research.

3.2. Similarities of the two theoretical perspectives

Much of the research presented in Chapter 1 served to characterise the slave systems within working memory. This focussed on research presenting a double dissociation between visual and verbal processes (e.g. Baddeley et al, 1975) and visual and spatial processing (e.g. Darling, Della Sala & Logie, 2007; Della Sala et al, 1999). This type of research is typically employed in conjunction with models of working memory which specify modality-specific slave systems. In contrast to this, much of the research presented in Chapter 2 approaches working memory by examining the trade-off between storage and processing and what this can add to the conceptualisations of working memory (e.g. Morey & Cowan, 2005). These conceptualisations of working memory, although eliciting different research traditions, share many similarities and are complementary.

As discussed in chapter 2, Cowan (1995, 1999, 2005) proposed a model of working memory in which a focus of attention is contained within activated working memory, which is in turn a subset of LTM representations. This was proposed in place of a multiple resource model put forward by Baddeley (1986; Baddeley & Hitch 1974) which is discussed in chapter 1. In response to the issues raised by models such as Cowan's, Baddeley (2000) added a new component to his model of working memory; the episodic buffer, introduced in chapter 1.

One of Cowan's main criticisms of Baddeley's model was that Baddeley specified that information is stored in working memory in separable, modality specific buffers. Cowan, however, proposes that information in working memory is simply activated LTM and the modality specific interference effects are caused by competition between stimuli with similar features. The addition of an episodic buffer to the multi-component model of working memory has taken steps towards linking the two perspectives, by providing a system that can hold information from different modalities and link them in a multi-dimensional code.

Several phenomena have identified and used to characterize the original Baddeley and Hitch (1974) model (see chapter 1 for a discussion on this). These phenomena have included ones in which verbal memory can be seen to decline in performance when coupled with articulation. However, in such studies there *is* a drop in performance but participants are still able to retain at least four items in verbal memory (e.g. Larsen & Baddeley, 2003). The contribution of LTM cannot account for this as participants with verbal STM problems show deficits in performance greater than those observed in normal participants under verbal interference (e.g. Vallar & Challice, 1990). The episodic buffer can account for this by utilising a multi-modal code to provide additional storage capacity.

One of the functions of the focus of attention in Cowan's model that is highlighted in chapter 2 is its ability to maintain elements of activated memory, the links between activated items and the links between these items and the current context to serve more complex cognitive activities. In the Baddeley (2000) model, this is achieved by the addition of the episodic buffer.

An important similarity between the viewpoints presented in chapters 1 and 2 is that neither regards working memory as a separable part of cognition. The models in chapter 1 define working memory in terms of functions and mechanisms whereas in chapter 2 working memory is based more on content which is seen as activated LTM. Furthermore, it is important to note that the models presented in chapter 1 don't deny the concept of activated LTM but propose further mechanisms that make slave systems functionally separate, while still highlighting the importance of

LTM in WM functioning. An overriding agreement is that both theoretical perspectives describe WM as a system which serves complex cognitive functioning.

To serve complex cognitive activities, whether viewed from the Cowan or the Baddeley viewpoint, a necessary feature of working memory is that of binding. Cowan's (2005) model the focus of attention is seen as the obvious system for binding to occur, in Baddeley's (2000) model, this is a function probably attributable (at least in part) to the episodic buffer. Both of these systems are proposed to require attentional/executive resources. The role of attention in the binding of features, objects and events is a point of much contention and is discussed below from both theoretical standpoints.

3.3. Types of Binding in Working Memory

Cowan (2005) proposes two major types of binding within visual working memory, the first of which is concerned with the binding between features of an object, the second is the binding between objects and the context in which they are presented. Baddeley (2007) also specifies two types of binding, the first of which is similar in nature to the first of Cowan's, proposed to involve binding based on gestalt-like properties of a visual scene, and it is proposed that this type of binding is relatively automatic. The second type of binding Baddeley proposes is predicted to be more effortful and involves collections of features being bound into *episodes*. This is similar to the second type of binding proposed by Cowan. The similarities between these two proposed types of binding seem to suggest that in both instances the first type of binding is likely to be within-modality and low-level, whereas the second type lends itself more readily to the type of binding which would occur across modalities and in the integration of higher-level representations perhaps integrating verbal or visual semantics.

A prominent question in the current working memory literature is whether binding is effortful, i.e. does it recruit executive or attentional resources? In terms of the Baddeley (2000) model, this is particularly important as it is postulated that executive functioning and the episodic buffer are intimately linked, to the extent that engaging the episodic buffer should also engage executive function (Allen, Hitch & Baddeley, 2009). The following sections will consider the nature of both low-level and high-level binding and the extent to which they demand executive resources.

3.3.1. Within-Modality Binding

The earliest relevant research on binding originates in studies of visual search and feature integration such as those by Treisman (1988). These studies have shown that the amount of time taken to search for a single feature in an array is largely independent of array size. In contrast when searching for a combination of features search time is directly affected by array size, suggesting the limit to working memory capacity may be the perception of the conjunction of features. Treisman (2006) went on to propose that attention is *necessary* in the maintenance of bound representations

As such, much of the recent research into the binding of visual features has focussed on the extent to which it demands attention or executive resources. Luck and Vogel (1997) employed a change detection procedure using visual arrays of objects, demonstrating that multiple features of multiple objects could be maintained at once. For example, when encoding orientation and colour of bars there was no difference in change-detection performance between single-feature and combined- feature conditions. They went on to show that performance was still not affected relative to single-feature conditions when participants were required to encode colour, orientation, size and the presence (or absence) of a gap in the stimulus. Thus indicating that at least four features can be integrated into one object, and regardless of the number of features the number of objects participants are able to maintain in memory is around four. Luck (2009) argues that integrated object representations are first created by perceptual processes *before* being stored in visual working memory.

Wheeler and Treisman (2002) replicated the work of Luck and Vogel (1997) but also required participants to make a judgement based on a whole test array not just one item probed in the test array and found that multiple colours within a single object had to be retained separately and as such made increased demands on working memory. However, overall their results suggested that it is almost as easy to retain two features as it is to just retain a single feature but that this is only true when the test is on a single item and not for a whole array. Cowan (2005) proposes that this could mean that the binding of features is automatic but access to the binding is limited. He suggests that a bound object must be *unpacked* for comparison of the features, so the number of objects stored is not the same as the number of objects which can be unpacked and compared to another object (probably with its own set of features) simultaneously.

Allen et al. (2006) investigated the attentional demands of binding using a dual task procedure. They required participants to view either four shapes, four colour patches or four coloured shapes and were then tested by being presented with a single probe item from the array and making a same/different judgement. They found that performance in the combined colour-shape condition was no different from the single feature conditions. They then went on to ask participants to perform serial 3 subtractions during the retention interval and again found no difference in performance between the colour-shape condition and the single feature conditions suggesting that binding was not demanding attention over and above that required for maintenance of a single feature object. Similarly, Gajewski and Brockmole (2006) showed that when a visual distracter was placed between the study and test arrays, there was no additional effect on bindings. Allen et al (2006) also tested memory for the items when presented sequentially with an interpolated backwards counting task. They found additional effects of binding when the final item in the sequence was probed and a disruption of the bound representation that increased as the number of items presented between presentation and probe increased. This suggests that perhaps binding does not demand additional attention but that the maintenance of a bound representation may be more fragile than single feature representations. This concept will be considered in Experiment 4 (Chapter 6), where changes in encoding duration will be linked with changes in stability of a representation.

Rossi-Arnaud, Pieroni and Baddeley (2006) required participants to perform a task similar to the Corsi Blocks task but in a 5 x 5 matrix. The sequence of locations was either random or symmetrical and this symmetry was either about the vertical, horizontal or diagonal axis. The only advantage that was observed was of vertical symmetry; performance was then reduced by the addition of an attention demanding task but this did not interact with the advantage of vertical symmetry supporting the view that binding based on gestalt properties was automatic. The same effect was observed in simultaneous presentation patterns of squares (similar in nature to visual matrix tasks), the only difference observed was a small but significant advantage for horizontal symmetry as well as the pronounced advantage for vertical symmetry observed in both tasks (Pieroni, personal communication, August, 2009). Both these results and those of Allen et al (2006) suggest a degree of processing that occurs before working memory processing, with the result that a task that impairs overall working memory does not necessarily prevent perceptual binding.

The work presented above by Wheeler and Treisman (2002) suggests that the role of attention in binding may be greatest at the point of retrieval, not encoding and maintenance. Carlyon, Cusack, Foxton and Robertson (2001) found that multiple auditory streams can be grouped together into an ignored channel or stream of information that are grouped together and bound on the basis or their similarities, but they found that this required attention. In contrast to this, using a very similar procedure, Macken, Tremblay, Houghton, Nicholls and Jones (2003) did not identify the involvement of attention. The difference between the two procedures may be the key here. Carlyon et al (2001) required participant to make a judgement on the bound material, and as such it had to be ‘unpacked’.

Cowan (2005) proposed a model of binding in which some attention may be required during the encoding phase of bound representation, but that it is possible to divide attention with another task (the limit to the amount that can be encoded is four items or chunks). The bound representations can be held without attention for short periods but interference (both internal and external) and competing stimuli mean attention is needed to retain these items for longer periods or in the face of secondary stimuli. This bears similarities to the Barrouillet et al (2004) TBRS model where attention is split between storage and processing. In retrieval, attention has to be divided between the internal representation and the probe stimulus, however, as seen in Wheeler and Treisman (2002) when the probe stimulus is the entire array (as opposed to just one item in the array being cued as either same/different) the memory load is much larger and the possibility of mistaken recombination of items during unpacking is increased.

Treisman and Gelade (1980) propose that selectively attending to the location of an object plays an important part in the integration of its features. They showed that single feature targets can be detected without localization but when targets consisting of a conjunction of features is to be detected, performance is only possible when the stimulus can be localised. However, this view was modified by Johnston and Pashler (1990) who showed that single feature targets do need to be localized coarsely. Treisman (1988) put forward a feature integration theory which specifies that focussed attention to an object's location is needed to bind an object's features but not to detect salient single-feature objects. This has been supported in a number of studies (e.g. Hopf, Luck & Girelli, 2000; Prinzmetal, Presti & Posner, 1986; Treisman & Sato, 1990)

Hyun, Woodman, Vogel and Luck (2009) tested this in an ERP study measuring the N2pc component, which reflects attention to a stimulus in visual search. They required participants to either detect the presence of a single feature target in an array, to coarsely localize it (in the top or bottom half of the array) or to localize it precisely. They demonstrated that localization required more attention than merely detecting a target but no difference between coarse and fine localization. This suggests that the binding of an object and location, even single-feature objects, may make demands on attention.

Allen et al. (2009) investigated whether the binding of colour and shape within an object is attentionally demanding when the features are presented in different modalities (one presented visually and one aurally). They demonstrated that features presented in different modalities showed the same recall performance as those presented in the same modality as a single stimulus. They also demonstrated no differential effect of spatial tapping or backward counting. Karlsen, Allen, Baddeley and Hitch (2008; cited in Allen et al, 2009) showed that the binding of colour and shape when presented in different locations was no more impaired by executive interference than the single-feature condition. These results suggest that binding can occur across locations without additional attentional effort and may lend itself toward a model in which binding and storage of bound representations are separate functions.

Cowan's embedded processes model is in part based on the work of James (1981), who put forward two types of attention; *ambient attention* which is automatic and *focussed attention* which is dependent on executive control. In the Cowan model ambient attention was developed into attention given to a stimulus without the involvement of the CE. Focussed attention is represented by attention under executive control. Allen et al (2009) propose that the episodic buffer could perhaps be linked to ambient attention with executive processes only becoming involved to bias contributions made by different features either within or between modalities.

The stimuli in the experiments presented thus-far consist of simple features of an object, combined together in an arbitrary manner. As such LTM representations of the objects are unlikely. Logie and Van Der Meulen (2008) point out that as the combination of features changes over successive trials, this may inhibit the development of a LTM representation and increase the amount of pro-active interference. This also has implications for the modelling of working memory, the performance of these tasks requires participants to remember feature combinations from the current trial and so relies on there being little or no trace of the combinations from previous trials, as such the memory component used to hold these bound objects must be vulnerable to displacement.

Treisman (2006) showed that even when feature combinations were presented together on up to 80% of trials there was no evidence of improved location change-detection for repeated feature-combinations, suggesting that the system maintaining bound features is perhaps a temporary memory system. Logie and Van Der Meulen (2008) go further in this claim, proposing that the lack of an impact of an intervening visual stimulus goes against the idea of the objects being represented in a system like Kosslyn's (2006) or Pearson's (2001) visual buffer and is in favour of the information being held in a passive visual cache. Logie and Van der Meulen (2008) go on to suggest that the insensitivity of bound visual features to irrelevant visual material is similar to Andrade et al's (2002) finding that visual STM is insensitive to Dynamic Visual Noise (DVN; see Experiment 9). This would suggest that binding of this kind is perhaps a passive or offline process, which will be discussed at length in Chapter 9.

Treisman and Zhang (2006) conducted a change-detection task in which the locations of the objects in the array (an irrelevant feature) were changed between study and test. They observed a large disruptive effect of location change at short maintenance intervals (i.e. less than 1 second) but found no effect of this change for longer maintenance intervals (more than 3 seconds), suggesting that the effect of changing irrelevant features occurs immediately following presentation. However the bound representation appears to be maintained with little impact of disruption. As such, it appears that the stored representation consists of only relevant features, suggesting the involvement of higher-level cognitive processes.

Overall, these data do lend support for bound information being stored in a temporary memory system, such as the visual cache. However, none of the research presented thus far discusses the binding of information beyond low-level visual or perceptual binding. Baddeley (2000) proposes that binding across modalities is a function of the Episodic Buffer and that the function of the buffer recruits executive/attentional resources. The research presented in this section goes against this assumption, however, the following section will consider a body of evidence concerned with binding across short-term and semantic representations and the extent to which this recruits executive or attentional resources.

3.3.2. Multi-Modal Binding and Chunking

The work of Luck and Vogel (1997) discussed above appears to suggest a capacity limit of around 4 items in working memory but that each of these can be made up of a large range of features and that the binding of these features is automatic. Wheeler and Treisman (2002) suggest there is a greater attentional demand of objects with bound features than single-features but only at the point of retrieval. Further to this Hyun et al. (2008) demonstrated that additional attention is required when localising an item.

However, all of the research presented thus far on binding is concerned with the binding of low-level features of objects such as colour, orientation, shape, location and gestalt properties like symmetry and appears to suggest that binding of this sort is not necessarily demanding of attentional resources. However, in the everyday use of working memory, integration of higher level information is also necessary, for example, the integration of LTM representations, strategic processing or the integration of information from other modalities, such as verbal representations of visual information.

Episodic memory has been shown to rely on attentional resources (Baddeley, Lewis, Eldridge & Thomson, 1984). A bound representation involving higher level semantic information is likely to be dependent on episodic processes and as such this kind of binding may be demanding of attentional resources.

Both of the theoretical perspectives put forward so far in the thesis have the fundamental assumption that working memory is capacity limited by the number of chunks that can be maintained at once (e.g. Miller, 1956; Cowan, 2001). In Miller's (1956) article *'the magical number seven plus or minus two'* he proposes that more items can be recalled when they are organised and grouped on the basis of pre-existing knowledge, a process he referred to as *chunking*. More recent research has provided evidence for a basic capacity limit in terms of chunks that can't be further grouped or phonologically rehearsed and qualified this capacity to be only around three or four unrelated items (Cowan, 2001). Baddeley et al (2009) specify that chunks are stored within the episodic buffer and that access to the buffer requires attention. In a similar account, Cowan (2005) proposes that attention is needed to form link between concurrently activated items when chunking. As such both of these accounts specify a role of attention in chunking.

Research explicitly investigating the binding of long-term and short-term representations in visual working memory is lacking. However, a body of evidence which related to the integration of higher level information comes from that on prose recall. Comprehension of text requires multiple representations, such as surface level syntactical information and deeper semantic information (Sachs, 1967). Tulving & Patkau (1962) made use of linguistic knowledge to examine capacity limits compared to isolated words and demonstrated that the more closely presented words approximated English texts (by increasing meaningfulness and grammaticality) the larger the chunks became on average. Cowan, Cohen and Rouder (2004) obtained similar results for lists comprising learned pairs of words, and propose that inter-word associations influence the sizes of recalled chunks but not capacity for the number of chunks.

Awh et al (2007) demonstrated that in change detection, accuracy declined as complexity increased. However, they also demonstrated that an increase in complexity is typically associated with an increase in similarity between target and distracter stimuli, as such reduced capacity may be due to comparison errors bought on by insufficient resolution of representations. They went on to show that correlations between change detection of simple and complex items were low, perhaps suggesting two distinct abilities: - One pertaining to the number of items which can be stored and one pertaining to the resolution of the representations. Scolari, Vogel and Awh (2008) investigated perceptual expertise in visual memory by looking at change detection performance for faces and propose that the increased change-detection performance for such representations to be due to them occupying less 'space' in working memory, allowing for greater resolution which in turn leads to lower probability of comparison errors and so a higher accuracy in change detection. It is possible that the work of Cowan et al (2004) presented above relates to a similar phenomenon, increased performance for associated word pairs reflects an increase in the *amount* of information within a chunk, not the *number* of chunks.

Baddeley (2007) reports a series of unpublished studies in which participants were required to tap keys in a random sequence while concurrently reading one of three prose passages matched in length but varying in difficulty. Reading itself did affect the key pressing but they found the difficulty of the prose passage had no impact on the randomness of the key presses. When the rate at which participants read the three passages was controlled, there was still no impact of difficulty on the key pressing. These effects were also replicated when the concurrent task was RT of key presses to a randomly emitted tone (both simple and choice reaction time). The authors interpret these results as showing that comprehension of prose is a much more automatic process than previously thought, however, their measures of memory for the prose were not extensive and as such may not have reflected finer differences in performance.

In a study allowing for greater control in the retention of prose, Jeffries, Ralph and Baddeley (2004) required participants to listen to and repeat back a sequence of simple sentences or a sequence of the same sentences but with the words scrambled. Further to this they heard and repeated each sequence three times to assess learning of the sequence. Learning was more rapid for the sentences relative to the scrambled words. A concurrent self-paced reaction time task in which participant had to press one of four keys in response to the location of visual stimuli did impair performance on the scrambled word condition and this impairment *increased* over the three repetitions of the sequence. For the sequence of sentences the impact of the key pressing task was reversed, it was greatest on the first trial and *decreased* across the three repetitions. In another experiment they introduced a third condition consisting of stories in which all sentences in the sequence were semantically related to one another, in this condition there was no effect of the concurrent task, regardless of the stage of learning. The authors attribute these results to the attentional demands of chunking. In the unrelated word sequences, chunking would only begin to occur with repeated presentations as there were no original links between words in the sequence, therefore the concurrent task has little effect on the initial trial and increasing disruptive effects across presentations. In the sequence of unrelated sentences, the binding that is necessary would be across sentences and the data suggest that this occurs on the first trial as this is where interference occurs. Overall these studies show a necessity for additional chunking and binding of sentences that are semantically incoherent, and this additional chunking increases task demands. This also suggests that binding in the episodic buffer is perhaps not demanding of executive resources (in the case of stories) unless phonological loop capacity is exceeded (in the case of unrelated sentences)

Baddeley et al (2009) attempted to limit the effects of prior knowledge by introducing a task they labelled *constrained sentence span* which uses a limited set of words across successive sentences which are put together into meaningful sentences that are increased in length by adding different adjectives and adverbs. The constrained set of words was used to build up proactive interference, forcing participants to rely on the most recent bindings of words. They showed a span of about 6 for random words, 8 for words when in a sentence from the constrained list and around 12 words from everyday sentences not taken from the constrained list. Using the same secondary task as in Jeffries et al (2004) they found very little impact, which the authors attribute to the involvement of the phonological loop in retention of the words.

In a further dual task paradigm, also reported in Baddeley et al (2009), both verbal and visuo-spatial secondary n-back tasks were developed, which they employed as a zero-back (demanding of the relevant slave system) and as a two-back which makes extensive executive demands. When combined with the constrained sentence task and the scrambled words there was an impact of the verbal zero-back and not the visuospatial zero-back on both tasks, suggesting constrained sentences and scrambled words employ the phonological loop. Both two-back tasks impaired performance on the word retention tasks, and this was equivalent for sentences and scrambled words, suggesting the benefit of chunkable sentences is not dependant on executive resources. To eliminate the support of the phonological loop, the words were presented visually and with concurrent articulatory suppression. Here the two-back task had a greater impact on sentences over words, suggesting that when access to the phonological loop is denied the central executive is needed to benefit from chunking.

A further area of binding research that has received interest is concerned with binding in elderly participants. Chalfronte and Johnson (1996) found that, relative to younger adults, the elderly showed poor performance in identifying the location of objects in a visual array but no difference in object identity or colour. The elderly were also poorer at recalling combinations of these features; from this study it is unclear whether this age-related change in binding abilities is dependent on attention. Naveh-Benjamin, Hussain, Guez and Bar-On (2003) found elderly participants were significantly worse than younger adults at remembering non-associated word pairs, but did not differ in their abilities to remember single words or semantically associated word pairs. Proposing that this reflected age-related changes in attentional capacity, they attempted to replicate this effect in young adults by requiring them to complete the task under conditions of divided attention but found no significant effects of divided attention (Naveh-Benjamin, Guez & Morom, 2003). Cowan (2005) proposes that this suggests that binding does not make demands on attention beyond that needed for the encoding of the individual features or objects. Baddeley (2007) proposes that the associative deficit in the elderly participants is perhaps due to a deficit in episodic LTM not attention.

Gilchrist, Cowan and Naveh-Benjamin (2008) looked at age-related differences at various levels of linguistic structure. These were 4 short sentences (each one clause); 4 long sentences (each two clause); 8 short sentences (consisting of the 4 long sentences being split into single clause sentences); 4 random sentences (single clause sentences scrambled randomly). If related sentences are chunked together into one unit then 4 long and 4 short sentences should be recalled equivalently despite the number of clauses. They found that older adults recalled fewer ‘chunks’ overall, but that they were equivalent to younger adults on the amount of information per chunk in that one chunk approximated one clause in both younger and older adults. The authors also found that the amount of information recalled was increased by chunking two short sentences into one longer one, but that it nowhere near doubled the informational stored. These data suggest that an age related deficit in associative memory is in retaining multiple unrelated items (i.e. separate chunks) when there is a lot of linguistic information.

Rudner and Ronnberg (2008) looked at speech recognition in hearing aid users. Speech recognition in known to involve the retrieval of lexical items from LTM on the basis of phonological information in the speech signal. By definition, this is a function of the episodic buffer. Speech recognition in distracting noise involves retrieval of lexical items from LTM on the basis of degraded phonological information. If the phonological information is distorted in relation to lexical representations in hearing aid users, it has been shown they rely on their general working memory capacity as measured by the reading span task (discussed in chapter 2). The increased reliance of general working memory capacity may reflect a greater load placed on the episodic buffer, it may be that episodic buffer processing becomes more effortful when there is a mismatch between perceptual phonological information and stored lexical representations in LTM. This is consistent with the conclusions drawn above by Allen et al (2009)

The research presented in this section has provided inconclusive results regarding the role of attention and executive resources in the binding of semantic and phonological information in memory for prose. It appears that when capacity of temporary memory is exceeded the central executive may be recruited to chunk together information and therefore reduce informational load. However, there is little research regarding the same semantic binding in the visual domain. The present thesis will employ visual matrix patterns which afford varying degrees of semantic support to investigate the nature of the integration or binding of LTM semantic representation and short-term visual representations.

3.4. Chapter Summary

The research presented in this chapter concerned with visual working memory is largely within modality and suggests that binding of this type is relatively automatic. The research presented on higher-level binding within memory for prose is far from conclusive - executive involvement is far less than would be expected but it appears that when participants are unable to rely on the phonological loop, binding of prose into chunks does draw on executive resources. Failure in binding of word pairs that are not semantically related in elderly participants relative to younger adults appears to be a result of deficits in episodic memory and not age-related changes in attentional capacity. It is clear, however, that there is a gap in the literature to investigate the nature of integration or binding of higher level resources in visuo-spatial task performance, and the degree to which this demands attention. This is the central focus of this thesis.

THESIS AIMS

Both Baddeley (2000) and Cowan (2005) propose that the integration of short- and long-term memory representations in visuo-spatial task performance would be demanding of executive resources. A method of investigating this is to employ novel stimuli which afford differing degrees of semantic representation. The work of Phillips and Christie (1977a; 1977b; Avons and Phillips, 1987; Phillips, 1974) suggests that visual matrix patterns afford both categorical (semantic) and pre-categorical (short term visual) representation. As such the present thesis will employ visual matrix patterns to investigate with how working memory takes advantage of long-term knowledge and to identify the extent to which forming 'chunks' of visual information is dependent on executive resources.

The first empirical study presented in chapter 4 is concerned with confirming the involvement of executive resources in a visual matrix pattern task relative to the Corsi blocks task, a conventional visuo-spatial working memory task known to employ executive resources (e.g. Rudkin et al, 2006). A further aim of the study is to utilise a visual STM task which makes relatively few demands on executive resources that can be employed throughout the thesis as a benchmark for visual STM performance.

The thesis will then concentrate more closely on visual working memory in Chapter 5 by creating two versions of the conventional matrix patterns tasks, one in which semantic support is more readily available and one in which it is less so. These will then be incorporated into a change-detection paradigm seen with increasing frequency in the literature (e.g. Alvarez & Cavanagh, 2004; Awh et al, 2007; Barton, Ester & Awh, in press; Luck & Vogel, 1997).

The first major series of studies will focus on identifying the characteristics of the two pattern sets created in chapter 5. The work presented in chapter 3 concerned with semantic support in prose recall (e.g. Cowan et al, 2004; Jeffries et al, 2004; Tulving & Patkau, 1962) suggests superiority in performance for stimuli with increasing levels of redundancy. However, both introductory chapters' viewpoints make it clear that a characteristic of fine pre-categorical visual information may be reflected in its retention over time and in the time course needed for semantic elaboration and its integration into the representation. Therefore, chapter 6 is concerned with identifying differences between the two pattern sets in overall performance, in stability of performance over increasing maintenance intervals and the impact of limiting encoding duration.

Following the characterisation of the temporal profile of both the maintenance and encoding of the visual tasks employed, a second block of studies will be reported in chapters 7 and 8 which aim to identify the implications the two pattern sets have for the functional architecture of working memory. Chapter 7 observes the impact of forcing the representations offline by using visual interference, as observed in Phillips and Christie's studies. This is combined with executive interference, as seen in Baddeley's (2007) work on prose recall and this effect is contrasted across the representations with differing degrees of semantic support.

The final empirical chapter, chapter 8, will be concerned with the broader issues of integration in visual working memory, namely verbal and attentional processes scaffolded in visual tasks with differing degrees of pattern redundancy, examined using a dual task paradigm.

Chapter 9 will then go on to provide a synthesis, linking the results observed across the five empirical chapters to the models of working memory discussed in the literature review.

All research reported in this thesis has been approved by the School of Psychology and Sport Sciences ethics committee at the university of Northumbria.

CHAPTER 4

Executive Involvement in Visuo-Spatial Task Performance

4.1. Chapter Overview

The present chapter aims to demonstrate, through the use of dual-task methodology, the involvement of executive resources in commonly used visuo-spatial tasks; namely, visual matrix pattern tasks and the Corsi Blocks Task. It also introduces a relatively new task, the Size Just Noticeable Difference task (Size JND) with the aim of demonstrating its relative independence from executive resources. A final aim of the chapter is to show that the executive involvement in these tasks is domain-general in nature.

4.2. Background

Research into the visual and spatial aspects of working memory (VSWM) has developed greatly over the last two decades and has provided a substantial body of support for the idea of separable visual and spatial systems (Klauer & Zhao, 2004; Logie, 1995; Logie & Marchetti, 1991; Logie & Pearson, 1997; Pickering et al, 2001; Tresch et al, 1993; See also Logie, 2003; Logie & Van der Meulen, 2008 for reviews of the VSWM literature). Two types of task employed to measure these components are tasks using novel matrix patterns (visual) and variants of the Corsi Blocks Task (spatial/sequential).

4.2.1 The Corsi Blocks Task

The Corsi Blocks Task (Milner, 1971) consists of nine blocks arranged irregularly which are tapped in sequences of increasing length. Participants are then required to replicate these sequences. This task was initially presumed to rely solely on the spatial working memory component of VSWM (Della Sala et al, 1999). However, with the increasing evidence of an intimate link between spatial working memory and attentional control (see chapter 1 for a discussion), there have been a number of studies implicating the use of extensive executive resources in the Corsi task (e.g. Awh & Jonides, 2001; Hamilton, Coates & Heffernan, 2003; Klauer & Stegmaier, 1997; Miyake et al, 2001; Thompson et al, 2006; Vandierendonck et al, 2004). For example, Vandierendonck et al (2004) showed that Random Interval Generation

(RIG; participants are asked to generate key presses at random intervals) and not fixed interval generation (FIG; generating key presses at fixed intervals) impaired span on a computerized version of the Corsi. The random element to the tapping has been shown to recruit executive resources (e.g. Vandierendonck et al, 1998) and as such the authors attribute this interference to competition for executive resources between primary and secondary tasks. Further to this, it has been suggested that executive involvement in this task is due to its sequential nature (Rudkin et al, 2007; Zimmer, Speiser & Seidler, 2003).

4.2.2. The Visual Patterns Task

Research into matrix pattern tasks has been less consistent. In the standard protocol of the Visual Patterns Task (VPT; Della Sala, Gray, Baddeley & Wilson, 1997) participants are presented with a matrix pattern with some of the cells filled in which is then removed, and the participants are asked to reproduce the pattern by marking off squares in a blank grid of the same size. Several studies have shown a separation of function between the Corsi and the VPT (e.g. Logie & Pearson, 1997). Della Sala et al (1999) used the two tasks and identified a double dissociation between them in brain damaged patients. The employment of selective interference in healthy adults has shown a double dissociation between the VPT and the Corsi in terms of their sensitivity to visual and spatial secondary tasks respectively. Della Sala et al then went on to propose the VPT as a relatively pure measure of visual short term memory. A large proportion of earlier research into novel matrix patterns supports this; Phillips (1974) showed evidence of forgetting with matrix patterns over just a few seconds, Phillips and Christie (1977a; 1977b) later reported a one item recency effect in recognition of sequences of novel matrix patterns and this pattern of performance lends itself quite readily to a temporary memory system underlying performance.

However, recent research has begun to show evidence of executive involvement in matrix pattern tasks. Miyake et al (2001) used a dot memory task with similar mnemonic demands to the matrix pattern task and found it to be correlated with executive task performance. Baddeley (1996) suggests that this involvement may be due to the fact that memorising dot patterns is not as practiced as maintaining information in the verbal domain and so has to draw more heavily on executive resources. Phillips and Hamilton (2001) demonstrated that performance of matrix pattern-like task followed an inverted U-shaped developmental trajectory with peak performance in young adults proposing that this is indicative of the development of executive processes. Andrade et al (2002) studied novel matrix patterns and showed them to be maintained over 36 seconds at 73% performance compared to 67% at a 4 second retention interval. This lack of decay is not representative of a short term visual representation (Williams, Beaver, Spence & Rundell, 1969). Hamilton et al (2003) also found a verbal fluency task impaired performance on a visual span task in adults and children, providing yet further evidence of executive involvement in the retention of novel matrix patterns. Thompson et al (2006) found executive task performance could account for 10% of unique variance in VPT task performance. In several of the above studies, researchers have identified the possibility for familiar objects or shapes to occur within matrix patterns. Cocchini, Logie, Della Sala, Macpherson and Baddeley (2002) used the VPT but removed patterns that contained obvious canonical shapes such as letters and numbers and found no difference in performance between immediate recall and a 15second delay (89.89% vs 89.72%). They also found a significant drop in performance with a digit preload and postulate it is due to some sort of verbal labelling of stimuli which prevents decay of the memory trace. This research suggests that the addition of verbal or semantic representations in matrix patterns as well as visual representations may be recruiting executive resources, this could be linked to the opportunity for higher level binding processes discussed in chapter 3.

In contrast to the above studies and perhaps in agreement with the earlier matrix pattern research, Rudkin et al (2007) found that random generation interferes with the Corsi Blocks task more than the VPT and when differences in experimental procedure were controlled for there was in fact no executive interference in the matrix pattern task and a large decrement in performance on the sequential Corsi task. Phillips (1974) suggested the pattern of results he observed with matrix patterns goes against the idea of verbal recoding of stimuli, as verbally represented material would not show decay over just a few seconds.

4.2.3. The Size Just Noticeable Difference Task

The present study will firstly aim to compare executive involvement in memory for visual matrices and the corsi task relative to each other and relative to a task presumed to make fewer demands on executive and semantic support or scaffolding. The Size Just Noticeable Difference Task (Size JND) was developed specifically to reduce the demands placed on executive resources (Phillips & Hamilton, 2001). In the Size JND task participants are presented with a square and following a short delay are shown a second square (typically offset from the original) and asked to judge whether it is the same size or different to the original square. Typically, this task is performed as a span task and the size difference gradually decreases across trials, until it is the smallest size difference a participant can reliably detect.

The developmental trajectory of this procedure has been shown to be more typical of slave system development (Gathercole, 1999; Phillips and Hamilton, 2001) compared to the development of the VPT task (Hamilton et al, 2003). Further to this, Thompson et al (2006) have also shown that the JND task did not correlate with measures of executive performance in healthy adults. Olsson and Poom (2005) suggest that visual STM may be limited to a single item when the stimulus is novel with no availability for categorical representation such as that seen in the Size JND task, which may be making greater demands on a process such as that proposed by Vogel et al (2001) which would be responsible for the storage of a single item with great precision or fidelity. This demand upon a representation of fine detailed coordinate, pre-categorical, information is more akin to a sensory representation within working memory (Cowan, 2008) and is subject to rapid decay (van der Ham, van Wezel, Oleksiak & Postma, 2007; Postma, Huntjens, Meuwissen & Laeng, 2006)

4.2.4. Executive Interference Paradigms

As mentioned in Chapter 1, there is debate in the literature as to the nature of the central executive with some authors proposing it to be a single pool of resources (e.g. Engle, Kane & Tuholski, 1999) and some specifying a fractionation of executive resources (e.g. Baddeley, 1996). A proposal put forward by Miyake et al (2000) is that the central executive is comprised of both specific and general resources. They put forward a three factor model (although the authors stress these are not put forward as the only executive functions) consisting of three separable (yet linked) executive functions, namely Shifting between tasks, Updating and Monitoring of the contents of WM and Inhibition of prepotent responses. These separable functions all appear to also tap a common pool of resources, Miyake et al propose that this could reflect the demands such tasks all make on a 'controlled attention' process as proposed by Engle et al (1999). Engle proposes a domain-free attentional system for maintaining representations within working memory in an active state or, in fact, suppressing those representations that are not task-relevant. Due to the possibility of domain-specific interference of executive secondary tasks, i.e. interference due to demands on updating and not domain-general demands which are proposed to be involved in the binding of higher level representations in visual working memory (e.g. Baddeley, 2007), the present study employs a selection of executive tasks, each of which is proposed to make both general and specific demands on separate functions. This is to highlight the general nature of the executive interference across the tasks. This relates to the task-impurity problem (see Miyake et al, 2000 for a full review) in which the range of demands made by a secondary task can make it difficult to attribute interference effects to a specific process. The three tasks employed here, although they all make separable executive demands, also share common, domain-general executive resources.

Bourke, Duncan and Nimmo-Smith (1996) characterise the *general* factor in dual-tasking as being limited to a fixed amount, split entirely between the two tasks being performed, and resulting in improved performance when its involvement in a given task increases. In order to tap the general factor in dual-tasking, several conditions must be met. Firstly, the two tasks must occur by differing input modalities; Treisman and Davies (1973) showed a decrease in performance when two concurrent tasks share input modality. Response should also occur in different modalities; Pashler (1990) demonstrated interference when tasks use the same motor response. Research presented in chapters 1 and 2 (e.g. Baddeley & Lieberman, 1980; Salamé & Baddeley, 1982; Della Sala et al, 1999; Darling et al, 2007) suggests that interference is greater between tasks requiring encoding and storage in the same modality.

Therefore, the present study was designed to assess the contribution of *domain general* executive resources to commonly used visuo-spatial working memory tasks, namely the Corsi blocks and the VPT. A third task is employed, the Size JND, which is thought to make relatively few demands on executive resources, and can therefore be used as a benchmark for VSTM. All secondary tasks in the present study are verbal-executive tasks, presented aurally and requiring an oral response. Whereas the three primary tasks are visuo-spatial in nature, presented visually and require a manual response.

It is predicted, that in both the Corsi and the VPT, the executive interference observed results from the recruitment of modality-general executive demands and that this interference will be greater when the demands of the secondary task are increased. It is further predicted that the Size JND will show a much smaller overall impact of secondary executive interference as it makes less complex demands.

4.3. Experiment 1: Method

4.3.1. Design

Table 4.1. Task combinations for the 15 conditions

			Primary		
		Single Task	VPT	Corsi	JND
Secondary	Single-Task	--	10	11	12
	Stop/Signal	13	1	4	7
	Plus/Minus	14	2	5	8
	N-Back	15	3	6	9
		Block 1	**Block 2**	**Block 3**	**Block 4**

Primary and *secondary* in the present study are defined by researcher interest. As the central focus of the study is the visuospatial tasks, these are defined as primary tasks and the verbal-executive tasks are referred to as secondary. The experiment was a within-subjects factorial design which involved participant completing all 15 combinations of three primary tasks and three secondary tasks and the completion of each task under single (conditions 10 – 15) and dual task conditions (conditions 1 – 9; see Table 4.1 for description of conditions). The dependent variables were proportion of correct responses and reaction time (to correct responses) for both primary and secondary tasks.

4.3.2. Participants

Twenty first year undergraduates (13 females; mean age = 22.75, standard deviation = 6.8 and 7 males; mean age = 20.37, standard deviation = 2.61) from the University of Northumbria obtained course credit for their participation

4.4.3. Materials

Primary Tasks

Matrix Patterns Task

In the initial phase of the task, a computerized version of a matrix patterns task was used, in which participants are presented with a white matrix with half the squares filled in black (presentation time 2000msec). They are then required to remember which squares are filled in and following a maintenance interval of 2000msec are required to replicate the pattern in a blank matrix of the same size (see figure 4.1 below). Participants complete 3 trials at each level of difficulty - entry level is 10 squares with 5 filled; this increases up to 26 squares with 13 filled, each square measuring 15mm x 15mm. Criterion for progression to the next level is 2/3 correct (as in the standard protocol; Della Sala et al, 1997) and maximum span level is taken as the last level at which participants met this criterion. The matrices are presented on a touch screen and upon response; the squares selected by participants are highlighted in black to provide feedback on the efficacy of the touch screen selection.

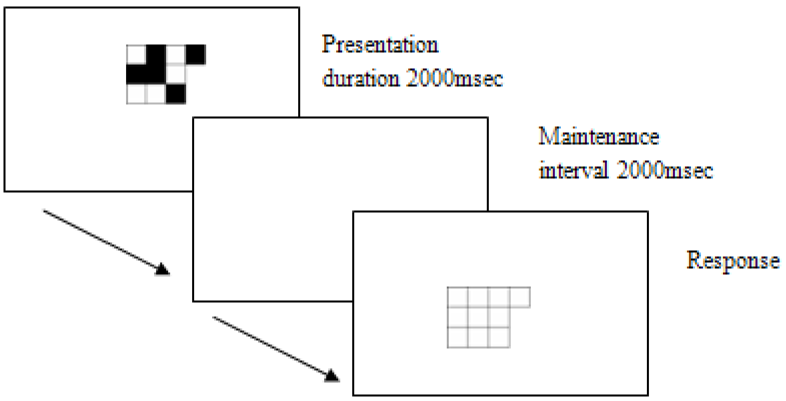


Figure 4.1. Task protocol employed for the recall version of the matrix pattern task.

In the test phase of the task, participants are presented with 10 matrices at their individual span level and the number of matrices correctly recalled was measured along with reaction time to correct responses. This is completed under single task (condition 10) and dual-task conditions (conditions 1 – 3).

Corsi Blocks Task

A computerized version of the task consisting of a series of 9 blocks (of 20mm x20mm) arranged irregularly, which are lit up in randomized sequences of increasing length. Each square changed from white to black and remains highlighted for 1000msec with an interval of 500msec between blocks. Following a maintenance interval of 2000msec the participant attempts to reproduce the sequence (see figure 4.2 below). When a square is selected in response, it is lit up in black for 250msec to provide feedback for participants.

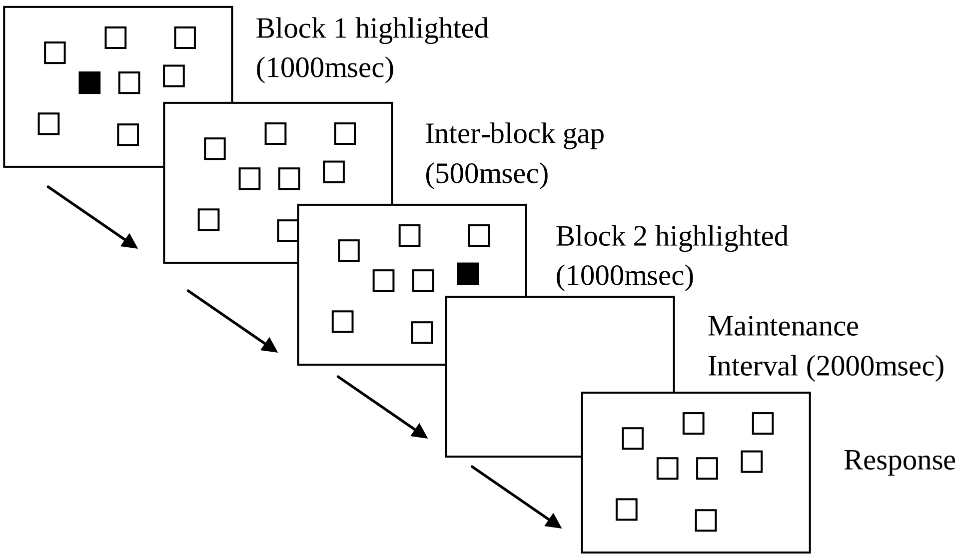


Figure 4.2. Task protocol employed for the recall version of the Corsi Blocks task at span level 2.

As in the matrix pattern task, participants completed 3 trials at each level of difficulty (defined by sequence length; ranging from 2 – 9 blocks) until performance fell below the 2/3 criterion for progression. They were then given 10 trials at their span level under single (condition 11) and dual task conditions (conditions 4 – 6).

For both the matrix pattern task and the Corsi, the stimuli were presented within an array of 320mm x 210mm and participants were seated to ensure a viewing distance of approximately 55cm.

Size Just Noticeable Difference (Size JND)

In this task participants are presented with a square for 2000msec. Following a 2000msec maintenance interval a second square is presented which is the same or 50, 40, 30, 20, 10 or 5% different from the original (see figure 4.3) depending on the difficulty level. They are asked to judge if the second square is the same or different using a same/different button on the screen. The squares were taken from a pool of 58 possible squares ranging from 12mm x 12mm up to 44.8mm x 44.8mm. This was to provide a varying pool of sizes to avoid LTM representations from developing through the procedure (Klauer & Zhao, 2004).

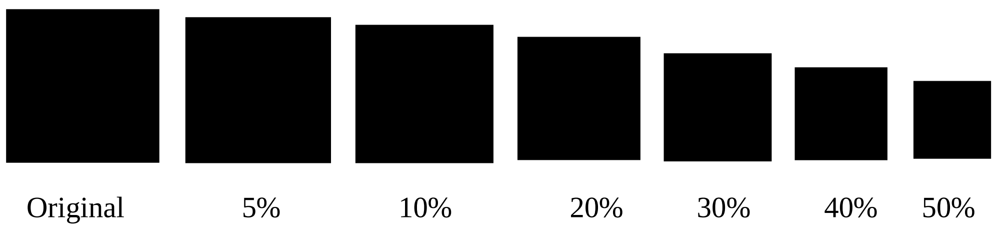


Figure 4.3. Examples of change in size for JND stimuli

Participants begin at an entry level of 50% difference and completed a maximum of 20 trials at each level (continuing up to a 5% difference) with the criterion for progression being 15/20 (binomial $p<.05$) to counter for guessing. Their maximum span level was taken as the maximum level at which they met this criterion, giving the smallest size difference the participant could reliably detect.

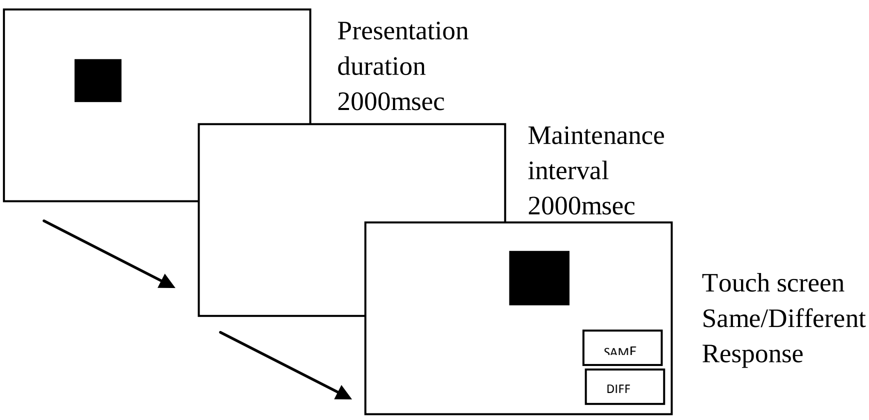


Figure 4.4. Protocol employed for the Size JND

In the test phase, participants were then given 20 trials at their span level under both single (condition 12) and dual task conditions (conditions 7 – 9). The stimuli were again presented within an array of 320mm x 210mm and participants were seated to ensure a viewing distance of approximately 55cm.

Secondary Tasks

Stop/Signal Task (Inhibition)

Adapted from that used in Miyake et al (2000), participants are presented with words (balanced for length and frequency; MRC Psycholinguistic Database, 1987) aurally by a computer at a rate of 1/2000msec; they then have to respond by categorizing the words as either animal ("yes") or non animal ("no") verbally.

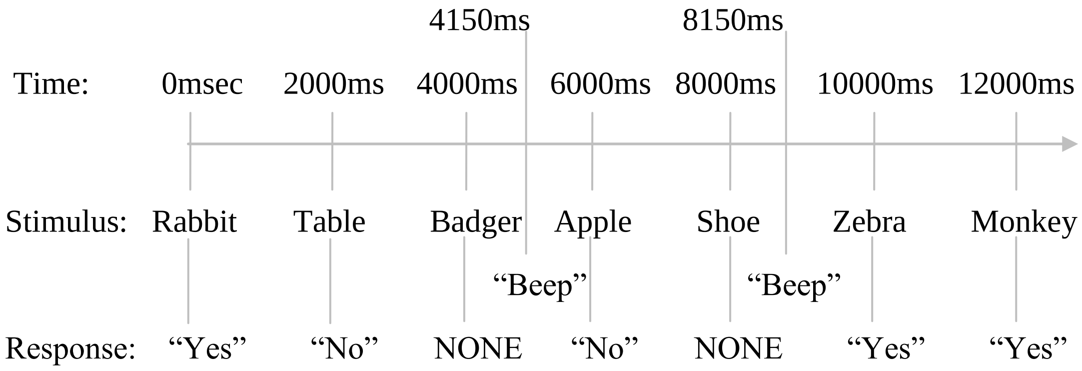


Figure 4.5. Stop/Signal protocol, shown as timeline from task onset with correct response.

Participants complete an initial block of trials in which they were instructed to categorize the words as quickly as possible without making mistakes, in order to build up a prepotent categorization response. In the test conditions participants are instructed not to respond when they hear a computer-emitted tone following the word but otherwise to keep performing the same categorization as before, this is performed under both single task (condition 13) and dual task (conditions 1, 4 and 7) conditions.

Plus/Minus Task (Set Shifting)

Also adapted from Miyake et al (2000), participants are presented with numbers, between 10 and 99 aurally by a computer at a rate of 1/3000 msec, they are then instructed to respond to each number by either adding or subtracting 3 and saying the product aloud. Participants must alternate between adding and subtracting across all trials. Participants were also given practice trials beforehand to ensure they were able to complete the task. Participants performed this under both single (condition 14) and dual task (conditions 2, 5 and 8) conditions.

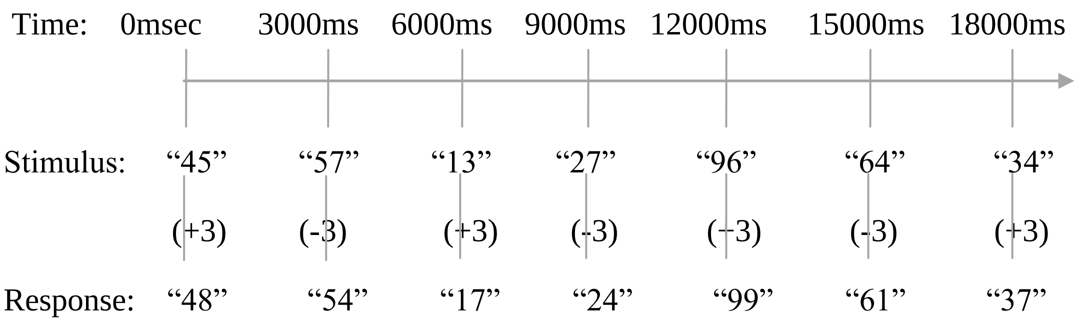


Figure 4.6. Plus/Minus protocol, shown as timeline from task onset with correct response.

N(2)-Back Task (Updating/Monitoring)

The n-back performed was a 2 back in which participants are presented with a sequence of single digits aurally by a computer at a rate of 1/1500 msec, and instructed to respond by saying “target” out loud when the digit presented is the same as one presented 2 beforehand. This was performed under single (condition 15) and dual task (conditions 3, 6 and 9) conditions.

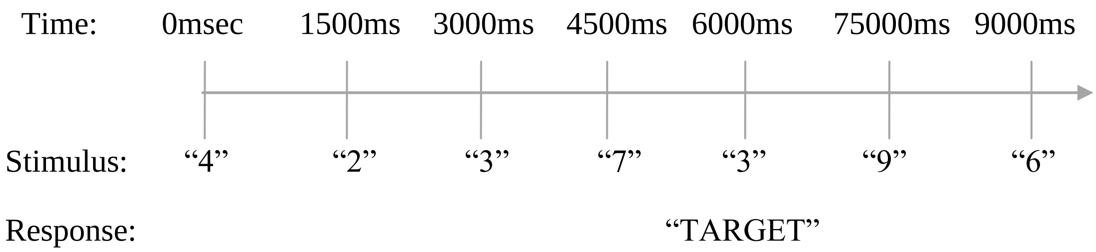


Figure 4.7. N-back task protocol as timeline from task onset, with correct responses.

4.3.4. General Procedure

The entire test session lasted approximately two hours. Task administration was blocked by primary task. At the beginning of each block participants completed the relevant span task, and then completed the four test trials (1 single task, 3 dual task) in random order. A fourth block was included in which participants completed the secondary tasks in single task conditions. The order of blocks was randomised for each participant and participants were given breaks between each condition.

In all dual-task conditions the secondary task began 10 seconds prior to the primary task onset, responses were only scored where both tasks were being performed.

The pace of the secondary tasks was chosen following a brief pilot study to ensure that there was sufficient time for participants to respond to each stimulus prior to the presentation of the next stimulus. In all tasks reaction time and correct responses were measured. In the dual task conditions, the secondary task lasted throughout the entire duration of the primary task.

4.4. Experiment 1: Results

4.4.1. Scoring

For all primary tasks, participants were taken to their individual span level (the criterion for assessing this is specified in the methods) and then given a set number of trials at their span, the scoring of which are discussed below.

The Matrix Patterns Task. For the matrix task, accuracy can be assessed by taking either the percentage of patterns replicated exactly or for each pattern, the number of target cells correctly identified. Both measures were taken but only the former (and more conventional) will be analysed. Reaction time is measured as the average time taken for participants to complete response on each trial to which they gave a correct response.

The Corsi Blocks Task. For the Corsi, either the proportion of correct sequences identified regardless of serial position or the proportion of sequences correctly recalled in terms of location and serial position can be measured. The latter will be reported as it captures the maintenance of serial order which is proposed to be the executively demanding element of the task. Again, reaction time will be taken as the average time taken to complete the full response on each correct trial.

The Size JND. For the JND, accuracy is measured as the number of trials participants correctly identify as either the same or different and reaction time is taken as the average time taken to make the decision on correct trials only.

The Stop/Signal Task. For accuracy, the proportion of trials where participants made a correct response (either a correct categorization or non-response for inhibition trials) was analysed. Reaction Time was not taken as a measure as the target trials were those in which participants correctly inhibited a response, as such no reaction time is available.

The Plus/Minus Task. Accuracy on this task could be measured in several ways. The number of trials on which participants successfully added or subtracted 3 or the number of trials on which they performed the correct function and gave the correct product. The latter was used, as this represented accurate set shifting and arithmetic. Reaction time was taken as the average amount of time between stimulus offset and response onset.

N-Back. On the N-back task, accuracy was measure in terms of hit rate and false alarm rate and a d' measure was calculated. Reaction time was taken as the time taken to correctly respond to a target, however, as the number of target trials was low (a maximum of 10), reaction time may not be a reliable measure.

4.4.2. Analysis of Mu Scores

In the present study, primary and secondary tasks are defined by researcher interest. As such participants' were not instructed to attend to one task above the other, therefore the analysis needs to accommodate for participants attentional focus. Baddeley, Della Sala, Papagno and Spinnler (1997) propose a measure of performance which averages out the cost of dual tasking across primary and secondary measures, called a *mu score*. An adapted formula for which can be seen below.

$$mu = \left[\frac{\left(\frac{ps - pd}{ps}\right) + \left(\frac{ss - sd}{ss}\right)}{2} \right] \times 100$$

Where *pd* and *ps* correspond to dual- and single- task performance on the primary task respectively. *sd* and *ss* correspond to dual- and single- task performance on the secondary task respectively. This gives the average proportional cost of dual tasking across primary and secondary tasks relative to single-task conditions. This is then converted from a proportion to a percentage; the larger a mu score, the greater the interference.

This calculation yields a mu score for every combination of task, accounting for a trade-off in performance between primary and secondary tasks

Analysis of percentage impact (mu) on correct responses

Table 4.2. Mean and standard Deviations for participants' Mu Scores representing impact of interference on accuracy for each combination of primary and secondary tasks

	Matrix Patterns		Corsi		JND	
	Mean	SD	Mean	SD	Mean	SD
Stop/Signal	27.41	27.12	30.70	20.89	10.24	9.13
Plus/Minus	52.59	17.31	48.71	17.59	17.81	11.95
N-Back	37.48	27.50	36.51	19.30	11.63	15.51

A 3 (primary task) x 3 (secondary task) repeated measures ANOVA revealed a significant main effect of primary task ($F_{(2,\ 38)} = 30.751$, $p < .001$ $\eta_p^2 = .618$). Bonferroni post hoc analysis revealed this to be due to the matrix pattern task and Corsi being significantly more affected by secondary interference than the JND ($p < .001$), but the impact of secondary interference on the matrices and Corsi were equivalent ($p = 1.000$). There was also a significant main effect of secondary task ($F_{(2,\ 38)} = 12.039$, $p < .001$ $\eta_p^2 = .338$), and Bonferroni post hoc analysis showed this to be due to plus/minus interference resulting in a greater drop in accuracy than stop/signal interference ($p < .001$) or n-back interference ($p=.031$; the latter two did not differ, $p=.524$) . The interaction was not significant ($F_{(4,\ 76)}= 1.803$, $p = .137$), suggesting the pattern of interference was equivalent for all primary tasks.

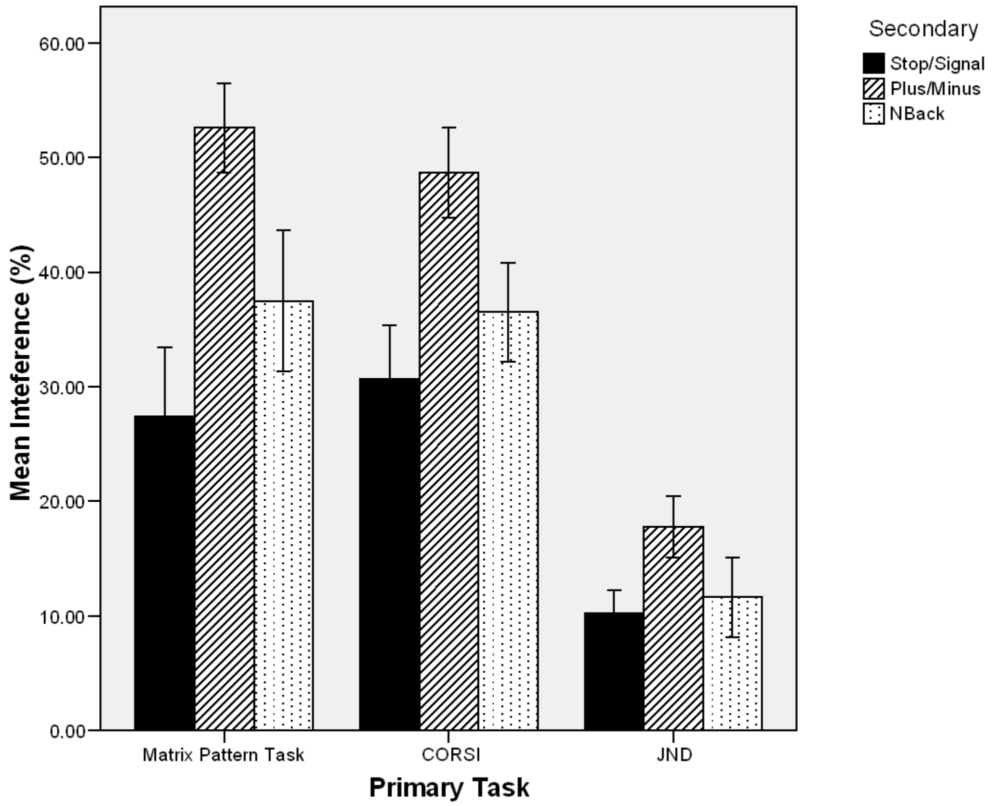


Figure 4.8. Mean interference (%) of 3 executive secondary tasks on 3 Visuo-Spatial Primary tasks, with standard error bars (+/- 1 SE)

Analysis of Percentage Interference (mu) on Reaction Time

Reaction times could not be calculated for the stop/signal task as the test trials (those involving inhibition of response) involve participants making no response, as such no reaction time data is available. For the n-back task, reaction time data is only available for hits (correctly identified targets). The number of hits per participant is presented in (Appendix A), as these are low for most participants the reaction time data is averaged over very few trials and as such is not a reliable measure for response time. As a result of this, the reaction time analysis is only considered for the primary task and is presented below as the percentage increase in reaction time under dual task relative to single task performance.

Table 4.3. Mean and standard deviations for participants' average percentage increase in RT (seconds) for each combination of primary and secondary task

	Matrix Patterns		Corsi		JND	
	Mean	SD	Mean	SD	Mean	SD
Stop/Signal	6.55	4.83	13.61	11.98	12.92	7.94
Plus/Minus	20.47	17.63	24.87	10.70	22.67	14.39
N-Back	12.02	12.74	13.78	10.87	12.04	13.97

A 3 (primary task) x 3 (secondary task) repeated measure ANOVA revealed no significant main effect of primary task ($F_{(2,38)} = 1.804, p = .179$). There was a significant main effect of secondary task ($F_{(2, 38)} = 17.664$, $p < .001$ $\eta_p^2 = .482$). Post hoc analysis showed this to be due the impact of plus/minus interference on reaction time being significantly greater than stop/signal (p<.001) and n-back (p=.001) interference. The interaction was not significant (F < 1) suggesting the pattern of interference was equivalent across the primary tasks on RT. It is proposed that the smaller impact of dual-tasking on reaction time relative to accuracy may be, in part, due to the tasks being computer paced.

4.5. Experiment 1: Discussion

Although the pace of the secondary tasks were adjusted to allow appropriate time for response, the plus/minus task was subjectively reported by participants to be more difficult than the other two executive interference tasks. The n-back task requires the participant to attend to the digits constantly but only required responses on about 15% of trials. The stop/signal task is designed to be a relatively automatic task which again only involved the inhibition of the prepotent responses on around 15% of trials. In contrast, the plus/minus task involved both storage and processing on every trial and had the added demand of requiring participants to switch between strategies of adding and subtracting which again would involve an element of storage and processing. As such the drop in performance on the plus/minus relative to the stop/signal task can be accounted for by a time-based resource sharing model (Barrouillet et al, 2004) in which memory traces decay when attention is occupied by concurrent activity, the more attention is occupied, the greater the decay. This would also lend itself towards an *energy* model of the executive interference (Cowan & Alloway, 2009) whereby greater demands of any secondary task are associated with a greater impact upon the primary task.

In line with previous findings (e.g. Vandierendonck et al, 2004), overall, the executive interference tasks had a major impact upon performance of the Corsi blocks task relative to single task performance, but interestingly the impact of executive interference was equivalent on the matrix patterns task, supporting previous research suggesting that matrix pattern tasks place significant demands on executive resources (e.g. Rudkin et al, 2007, Exp 1; Thompson et al, 2006). However, given the presence of the concurrent secondary executive demands throughout the primary task duration these results do not differentiate the importance of executive resources for the encoding, consolidation or maintenance of visual working memory (Stevanoski & Jolicoeur, 2007; Vogel, Woodman & Luck, 2005) versus maintenance or retrieval of primary task information. Relative to both of these tasks the Size JND performance remained largely unaffected by executive interference supporting the increasing body of research suggesting it is a relatively pure measure of low level visual STM (Thompson et al, 2006) but perhaps to a small extent dependent upon conscious attentional resources (Cowan, 2008; Offen, Schluppeck, Heeger, 2009).

The executive resources involved in the matrix pattern task and perhaps the inconsistency in the literature can be explained by the chunking of parts of the pattern. It was discussed in chapter 3 that information in working memory can be ‘chunked’ together into fewer units to increase the amount of information that can be held in memory, Jeffries et al (2004) propose chunking to be executively demanding. It is possible that in the memory for matrices, long-term semantic information may be integrated into the working memory representation of the pattern to group together cells into familiar forms. This is similar to the research on memory for prose (e.g. Baddeley, 2007) in which words are grouped together into semantically related chunks to allow for a prose memory which far exceeds the capacity of verbal short term memory. Although there is still debate in the literature whether the chunking of verbal information on the basis of semantics is executively demanding (as discussed in chapter 3), it is possible that this is what recruits executive resources in matrix pattern tasks. As participants were performing at span level, it is likely that central executive resources would be recruited to chunk together information and reduce information load (e.g. Rudner and Ronnberg, 2008).

As discussed in section 4.2.2, there is inconsistency within the literature as to the degree to which verbal and executive resources have been shown to be involved in matrix patterns tasks. Several studies do acknowledge the possibility of verbal coding in matrix pattern tasks and typically try to control for this my removing patterns which represent familiar shapes or objects (e.g. Andrade et al, 2002; Rudkin et al, 2007), however, very few studies have been conducted which systematically limit or measure the extent of their involvement. Some studies have looked at training and familiarity with novel visual information (e.g. Olson & Jiang, 2004; Chen, Eng & Jaing, 2006), but have not systematically varied the structure of stimuli, merely the number of times each stimulus is presented.

In Logie's (1995) adaptation of the original Baddeley and Hitch (1974) model the content of working memory was viewed as being activated LTM information. Thus, he stressed that there was no direct link between working memory and perception, that the contents of working memory incorporate some form of interpretation based on prior knowledge and that working memory provides a 'mental workspace' within which activated material is retained and manipulated. In this model, executive functioning is responsible for coordinating and manipulating information held in the slave systems or generated from LTM. The ability to incorporate information in LTM with that in visual working memory has been shown to be crucial for chunking and therefore increasing the total amount of information stored (e.g. Jackson & Raymond, 2006; Olsson & Poom, 2005). This would suggest that performance of matrix pattern tasks would be facilitated by the presence of familiar forms in each pattern, and that the incorporation of existing knowledge could be responsible for the involvement of executive resources. This visual semantic support was made explicit in the Baddeley (2000) amendment to the original working memory architecture.

Brown, Forbes & McConnell (2006) explicitly acknowledged the possibility of verbal coding in the VPT and separated it into subsets of High and Low verbalizable patterns and found a reliable difference in ratings of verbalizability along with an increase in task performance associated with the highly verbalizable patterns.

As discussed in Chapter 1, the architecture of WM must be able to accommodate the simultaneous presence of dual representations. Pearson (2001, 2006), in addition to Quinn (2008) has argued for the requirement of two WM processes in tasks such as the serial recall of matrices where dual representations are present; a process which maintains the last item in relatively fine pre-categorical detail and a process with LTM support which may maintain in categorical form, the earlier items. In Baddeley's (2000) model the VSSP process is identified for visual mnemonic processing and an executive subsystem was introduced, the *Episodic Buffer*, a process capable of the binding and integration of multiple formats. It is possible that categorical representation could be maintained within the Episodic Buffer. Indeed given the dual representations, some form of binding process of low level representation with semantic categorical representation may be required for the participant to maintain a stable representation in the face of the fragility of working memory episodic bindings (Allen et al, 2006: Logie et al, 2009). The need for an executively driven binding process would also implicate executive resources in the visual matrices task performance. It was highlighted in chapter 1 however, that Pearson (2001, 2006) and Quinn (2008) would consider the presence of dual representations within a conceptual framework more akin to Kosslyn's (1994) *Visual Buffer* and *Pattern Activation System* processes. In Cowan's (2005) model of working memory, categorical information could be activated and maintained in either STM or within the focus of attention. Simultaneously, partially processed sensory information relating to a stimulus can be maintained in fine detail. The further semantic elaboration and chunking of this sensory information would be executively demanding.

4.6. Chapter Summary

This chapter has demonstrated that the impact of executive interference on memory for matrix patterns is equivalent to the impact seen on the Corsi. It has also been demonstrated that the impact on the Size JND is relatively small. Chapter 6 aims to demonstrate that one possible source of the executive involvement in memory for matrices come from the presence of dual-representation of the patterns, in both categorical and pre-categorical forms. Chapters 7 and 8 attempt to differentiate the importance of the consolidation and maintenance processes in visual matrix task performance. To allow for this, two sets of matrix patterns will be constructed in chapter 5, one which lends itself to categorical representation and one which does so to a lesser extent.

CHAPTER 5

Semantic Re-Classification of Matrix Patterns

5.1. Chapter Overview

The previous chapter demonstrated the involvement of extensive executive resources in short-term memory for visual patterns and postulated that this was due to the presence of dual representations of the matrices in working memory, specifically representations in pre-categorical and semantic forms. The present methodological chapter aims to create two sets of visual matrix patterns for use in the remainder of the thesis, one which readily affords semantic coding and one in which it is more difficult to do so.

5.2. Background

As discussed in the previous chapters, Phillips and Colleagues developed a paradigm for visual serial memory using matrix patterns. Typically the items are presented in reverse serial order such that the last item presented in the series will be the first item tested using a recognition procedure. Using this procedure Phillips and Christie (1977a) showed a one item recency effect whereby performance on the last item in the series was significantly greater than all other items but that performance on the earlier (pre-recency) items was still above chance. Phillips (1983) suggested that this recency effect is indicative of a visual short term memory limited to a single-item

Researchers have been interested in the processes involved in memory for matrices for more than 50 years. Attneave (1955) investigated the improved memory performance for regular figures over and above irregular ones. Typically, regular figures have a lower information load than irregular ones, as such Attneave investigated whether the superiority observed persists when information load is held constant. He assessed redundancy in matrices by varying symmetry in the stimulus, observing memory performance in immediate reproduction, delayed reproduction and recognition paradigms. He demonstrated that in all cases symmetrical patterns were remembered better than asymmetrical patterns of the same number of cells and that random patterns were more difficult to remember as their complexity (defined by matrix size) increased. He also found that for all forms of the task, when information load was held constant, the advantage for symmetry was eliminated. This Suggests that the superior mnemonic performance relates to the reduced information load associated with familiar forms.

Chipman (1977) found that within the literature there is little consistency with definitions of complexity within visual patterns. He showed that the definitions used can be reduced to two broad categories; one representing quantitative factors and one representing structural factors. Ichikawa (1985) investigated this further, assessing different factors contributing to participants ratings of complexity of dot matrices (similar to filled matrices in their mnemonic demand). Participants were required to generate matrices of 4 x 4 cells with 8 filled for ratings of complexity ranging from 1 through to 7. Using factor analysis and multiple regression the authors demonstrated that there were two factors underlying individual differences in the ratings of complexity. These related to the two factors identified by Chipman (1977). Firstly *quantitative complexity* defined by factors such as the concentration of filled cells within the matrix, the number of clusters etc. The second factor, *structural complexity,* was defined by symmetry and other measures of redundancy relating to higher cognitive processing.

Ichikawa (1985) then showed that when presentation time was reduced, participants tended to only judge complexity based on quantitative features. In contrast, correlations between measures of structural complexity and overall ratings of complexity increased with presentation duration (50msec, 200msec, 1000msec and 4000msec). They went on to propose that in complexity judgements processing of quantitative and structural factors take place in parallel with the latter taking longer. In support of this, Chipman and Mendelson (1979) conducted a developmental study and showed that when making complexity judgements, quantitative factors significantly contributed at all ages. However, the contribution of structural factors increased with age, in line with the pattern of development seen with executive resources.

In line with this, Avons and Phillips (1987) propose two types of description within visual patterns, the first of which they term *visuospatial description* which refers to the visual appearance of the matrix or spatial relationships between the pattern elements. Importantly, a visuospatial description can also make use of high-level representations such as familiar forms within the pattern, these can be accommodated into the pattern by making modifications to the internal representation of the familiar form. Avons and Phillips propose that the integration of high level representations into a visuospatial representation should increase the capacity for such patterns. The second level of pattern description put forward is *semantic description*, this level of representation occurs without visuospatial description. This is achieved by recognising pattern elements as familiar forms, this knowledge is then preserved until test but any specification of spatial modifications to the internal representation are lost, leaving performance reliant only on categorical or semantic information.

Avons and Phillips therefore propose that the recency performance for visual patterns may comprise of basic visuospatial representation in a visual store *and* high level representations from long term semantic memory, leaving pre-recency performance dependant only on the latter type of representation. However, Walker, Hitch and Duroe (1993) demonstrated that even pre-recency performance is negatively affected by visual similarity, and therefore may be reliant on visuospatial description to some extent. It is therefore possible that both recency and pre-recency performance is dependent on visuospatial and semantic descriptions but with differential dependencies on the two forms of description. Avons and Phillips (1987) examined memory performance using visual matrix patterns, employing visual interference in the maintenance interval (to assess representation of the pattern in long-term visual memory) and with an unfilled maintenance interval (to assess short-term visual memory). They demonstrated that long-term visual memory performance was improved when there was a large change in semantic classification between target and distracter and with an increase with presentation time which they propose is indicative of an increase in the proportion of the pattern that can be accommodated in a categorical representation.

Kemps (2001) examined both quantitative and structural complexity with the corsi blocks task and showed that span was inversely related to the number of blocks in a sequence (quantitative complexity) but that it was also improved by putting the blocks in a matrix rather than a random pattern (structural complexity). She further investigated this by assessing redundancy in the path made by the sequence of blocks, when the path is more structured memory performance increased, perhaps suggesting a more redundant path is benefiting from LTM representations for redundancy such as symmetry whereas a complex path has a greater reliance on visual short term memory. Further to this, Kemps showed that training on complex paths could lead to performance levels akin to the structured paths.

As shown in the previous chapters, no one has as of yet, provided sufficient details of the relationship between visual STM and visual LTM representations of an object in working memory. Olson and Jiang (2004) assessed familiarity within novel stimuli using a training paradigm, based on the premise that over repeated presentations participants would be able to build up an LTM representation of the array. They found that change detection performance for a familiar array was no better than performance for a novel array. In this experiment, however, there were 6 very similar arrays, each only presented 24 times. This level of 'familiarity' may not be sufficient to characterize processes involved in every day change detection of familiar arrays. Items that are typically familiar in real life situations have been seen hundreds, perhaps thousands of times over a lifetime and as such may have much stronger semantic links than those induced by Olson and Jiang (2004). Similar results were observed by Chen et al (2006) in training in familiarity for novel polygons, but this is also an artificial level of familiarity. Buttle and Raymond (2003) observed change-detection performance for familiar, weak-familiar and unfamiliar faces and found familiarity improved performance. The authors take this as evidence for the contents of visual STM being activated visual LTM representations; however, Luck (2009) suggests that the scaffolding of performance in such studies may reflect the use of non-visual semantic representations.

As discussed in chapter 4, research using matrix patterns suggests that the executive involvement may be due to the possibility of consolidation (Stevanoski & Jolicoeur, 2007) or construction of dual codes or the opportunity for participants to create multiple representations of the patterns. Alternatively, executive resources may be required for the construction and maintenance of the fragile bound representations derived from the integration of low level and categorical information. Work by Avons and Phillips (1987) and Awh et al. (2007) would suggest that both pre-categorical and categorical object-based representations could be formed within working memory and that the construction and integrated maintenance of the categorical representations may be what demands executive resources, as demonstrated in Chapter 4.

Brown et al (2006) systematically varied the degree to which VPT patterns would afford verbal semantic support and demonstrated a difference in performance for patterns which lend themselves towards this dual-representation. The present study aimed to systematically vary one element of a matrix pattern which may facilitate the construction of a categorical representation much in the same way as Brown et al (2006) only rather than specifying the representation as a verbal one, the present study is allowing for the representation to be either verbally or visually semantic in nature, more akin to what Avons and Phillips (1987) termed *semantic familiarity*.

5.3. Method

5.3.1. Participants

An opportunity sample of 78 students from Northumbria University took part (mean age 26.9 years).

5.3.2. Materials

A minimum of 80 unique patterns were created for each level of the matrix task (5 to 15), giving a total of 978 original patterns plus the 84 patterns included in the original VPT task (Della Sala et al, 1997). Participants were also given a response sheet containing 7-point rating scales for each pattern and space to provide a full description.

5.3.3. Design and Procedure

Participants were tested in self-paced sessions lasting 45 minutes and asked to rate as many patterns as possible in that time. Standard instructions (see appendix B) were given to the participants asking them to indicate how much of the pattern they felt they could apply meaning to on a scale of 1 (none of the pattern) to 7 (all of the pattern). This was defined as when all or parts of the pattern resembled “familiar objects or symbols” or where they recognized shapes or configurations which they may find difficult to explicitly name. They were also asked to try and describe how they remembered the pattern. In the coding of the descriptions, the same rules were adopted as used in Brown et al (2006).

5.4. Results

Table 5.1. Mean (and standard deviations) of semantic ratings for high and low semantic patterns and t and p values for the difference between levels of semantics at each level of complexity.

Level	Low Semantic	High Semantic	t	P
	Mean (sd)			
4	4.58 (0.52)	6.39 (0.50)	-11.277	<.001
5	4.63 (0.25)	5.94 (0.20)	-18.057	<.001
6	4.60 (0.17)	5.98 (0.29)	-18.126	<.001
7	3.07 (0.21)	5.44 (0.48)	-20.306	<.001
8	3.01 (0.25)	5.20 (0.46)	-18.747	<.001
9	2.50 (0.31)	4.73 (0.60)	-16.217	<.001
10	2.72 (0.31)	4.46 (0.30)	-17.989	<.001
11	2.25 (0.21)	3.89 (0.41)	-15.853	<.001
12	2.05 (0.17)	3.61 (0.37)	-17.369	<.001
13	2.06 (0.17)	3.56 (0.35)	-17.388	<.001
14	2.00 (0.18)	3.41 (0.36)	-15.583	<.001
15	2.16 (0.18)	3.59 (0.19)	-24.014	<.001

9303 ratings were obtained in total. For each level of the matrix patterns task the patterns with the top 20 and the bottom 20 ratings were selected. Patterns receiving an average rating of 7 were automatically excluded. Patterns receiving a rating of 7 by one or more participants were screened for those which represent a single shape, and so could be readily represented in verbal working memory. Average ratings for the final patterns were entered into a 2 (High vs Low semantic) x 11 (Level of Complexity; defined here by pattern size) ANOVA which revealed a significant main effect of level of complexity ($F_{(11,456)} = 407.059$, $p < .001$ $\eta_p^2 = .908$) which reflects the decrease in semantic coding as the level of complexity increases. There was also a significant main effect of pattern set, ($F_{(1,456)} = 3246.085$, $p < .001$ $\eta_p^2 = .877$). As expected, low semantic patterns (mean = 2.969) had significantly lower semantic rating than high semantic patterns (mean = 4.683). Finally there was a significant interaction ($F_{(11,456)} = 12.313$, $p < .001$ $\eta_p^2 = .229$), which was shown to be due to the fact that in the low semantic patterns there is a no difference between levels 4, 5 and 6 ($p > .05$) and a large drop between levels 6 and 7 ($p <. 001$), whereas in the high semantic patterns the decrease in the ratings is gradual across the levels. Despite this interaction, the high and low semantic patterns were significantly different from one another at all levels of complexity, as shown above in table 5.1.

5.5. Stimulus Sets

Two tasks were created, one consisting of high semantic patterns and one of low semantic patterns. Each task was made up of 20 patterns at each level of complexity, ranging from level 4 (8 cells, 4 filled in black) to level 15 (30 cells, 15 filled in black).

To create a recognition version of the matrix pattern sets an alternative version of each pattern was created (see figure 5.1) to allow for same/different judgments. This was done by moving one square in the matrix by one cell strategically to avoid any large changes in obvious ‘chunks’ in the pattern and to avoid the creation of new canonical shapes.

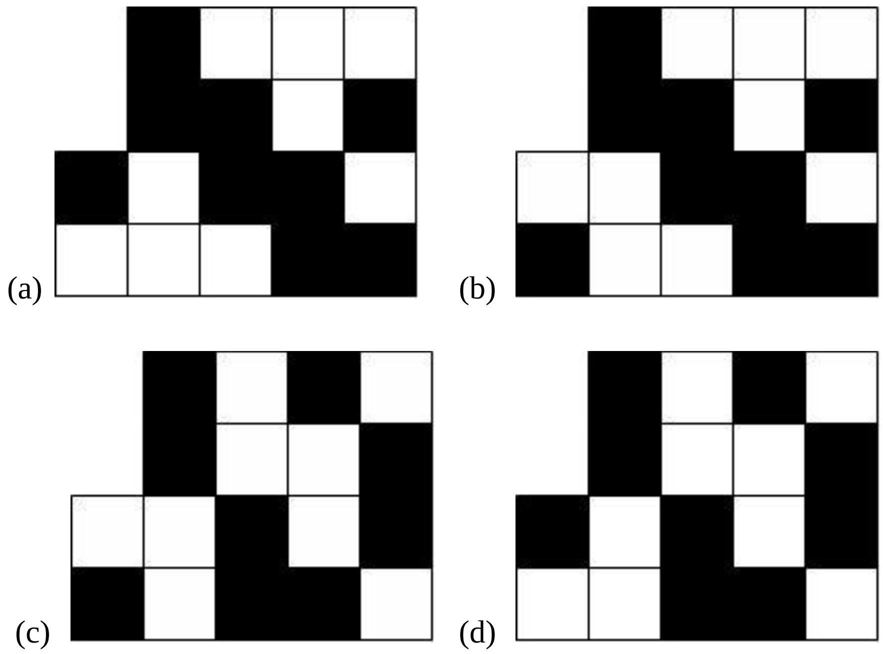


Figure 5.1. High (a) and Low (c) semantic patterns and the ‘different’ versions of each: High (b), Low (d).

Internal consistency of the two pattern sets was tested, in a sample of 48 participants Cronbach's Alpha was shown to be .982 for the high semantic pattern set and .983 for the low semantic pattern set.

5.6. Chapter Summary

The present chapter has served to create two forms of the matrix patterns task, one which lends itself towards semantic representation and one in which the possibility to do so is limited. Performance on these two variants relative to the Size JND (which makes relatively few demands on executive resources) will be explored in both blocked and randomized designs (Experiments 2 and 3). A further experiment will then be reported in which the presentation or encoding duration of the stimuli will be reduced to deny the opportunity for semantic elaboration of the stimuli and the subsequent performance across the tasks contrasted (Experiment 4).

5.7. Structure of chapters 6, 7 and 8

For the remainder of the thesis, the high and low semantic matrix tasks will be used along with the Size JND task, shown to make relatively few executive demands in chapter 4. All results sections will follow a standard structure to allow for comparison between studies, as follows:

1. Firstly, a table of raw scores will be presented in terms of average span level achieved, these are represented as follows:

Size JND

Span level is defined as the smallest percentage change in size between study and test stimuli that participants can reliably detect at an above chance level (binomial $p < .05$). The highest performance a participant can achieve is 5%, the lowest is 40% (50% in Experiments 5, 6 and 7)

High and Low Semantic Matrices

Span level here is defined as the largest pattern size a participant can reliably recognise at an above chance level (binomial $p < .05$). Entry level is level 5 (10 cells, 5 filled in black) for Experiments 2, 3, 4, 8 and 9 and 4 (8 cells, 4 filled in black) for Experiments 5, 6 and 7. Maximum span in all experiments is 15 (30 cells, 15 filled in black)

2. A comparison between the two forms of matrix pattern task will be conducted. This will be a 2 (level of Semantics) x 3 (Maintenance Interval) mixed ANOVA.

Bar charts will be presented to compare high and low semantic matrix performance across three maintenance intervals. A standard scale will be used to allow direct comparison across the studies, appendix C contains all bar charts to allow for ease of comparison

3. The effect of increasing maintenance interval will be analysed for each task. To do this a one way repeated measures ANOVA with 3 levels (maintenance intervals) will be conducted for each task, the p values will be Bonferroni corrected to compensate for using three separate analyses.

4. Scores will then be standardised (within task, across maintenance intervals) to allow for a comparison. As the Size JND and the matrix tasks are fundamentally different tasks, this is largely a qualitative comparison of decay functions. These will be presented in a graph for each experiment, again with a standard scale to allow for ease of comparison. Appendix D will contain all standardised graphs.

5. Finally, Experiment 2 will provide a baseline of performance of the three tasks across the three maintenance intervals in the absence of any interference. As such, for all subsequent experiments a final analysis will be conducted for each task comparing these baseline results to the results of Experiment 2.

CHAPTER 6

Maintenance and Encoding of Visual Matrix Patterns

6.1. Chapter Overview

This chapter is designed to identify the temporal characteristics of the encoding and maintenance of the two forms of the matrix pattern task created in the previous chapter. As demonstrated in Chapter 4, relative to matrices, the executive involvement in the Size Just Noticeable Difference (Size JND) paradigm is greatly reduced, therefore supporting a growing body of literature suggesting it is a relatively pure measure of VSTM. As such the Size JND will be employed in the present chapter as a benchmark for the temporal characteristics of VSTM, with which the two forms of matrices can be compared**.**

6.2. Background

Brown et al (2006) looked at performance differences in the original VPT when the patterns were separated into high and low verbalizable patterns and demonstrated a small yet significant difference in span performance between the two sets of VPT stimuli (Mean Span for High = 10.08; and for Low = 8.72). However, if the semantic load manipulation is effective, then the low semantic set will be less able to take advantage of available semantic categorization and support. As such, binding will be compromised and this pattern set may show temporal decay characteristics more similar to the Size JND which, because of its fine coordinate resolution capabilities, is expected to show rapid decline in efficacy over a short period of time (van der Ham et al, 2007; Postma et al, 2006). In contrast the high semantic matrices set should be able to take advantage of this semantic support, have a less fragile representation and thus demonstrate equivalent performance level across a sustained maintenance interval (Andrade et al, 2002).

Pearson (2001) stipulates that information represented in a visual buffer (a pre-categorical process) decays rapidly. It was suggested in chapter 1 that the recency effect seen for matrices (e.g. Phillips and Christie, 1977a) could be attributed to representation in the visual buffer. Further to this, Cowan et al (1990) propose that shifting attention to the stimulus may allow for greater activation of semantic information associated with the stimulus, which in turn will increase stability (Cowan, 1988). It is therefore possible that the high semantic patterns will show greater stability as there is opportunity for richer semantic links.

6.3. Experiment 2: Maintenance in a Blocked Design

Change detection paradigms have become increasingly popular in the literature in recent years (Luck & Vogel, 1997; Alvarez & Cavanagh, 2004; Awh et al, 2007; Barton et al, 2009). The involvement of non-mnemonic processes and response systems are minimised, and they have been proposed as a more valid methodology for assessing visual working memory as change detection is perhaps closely linked to the way visual WM is employed in everyday situations (Luck, 2009). Change-detection paradigms involve the comparison of VSTM representation of an array with a perceptual representation of a test array. In the environment visual input is often disrupted by blinks and eye movements and as such VSTM can be employed to compare the visual scene before disruption (held in VSTM) and the visual scene after. The present study will employ the tasks created in the previous chapter in a change detection paradigm to identify the temporal profile involved in the maintenance of the representations in the two forms of the matrix pattern task relative to the Size JND.

6.4. Experiment 2: Method

6.4.1. Design

A mixed design was used in which the visual memory task was a between subjects factor with three levels; Size JND, low semantic Matrices and high semantic Matrices. Maintenance interval was the within-subjects factor with three levels; 4.5, 8.5 and 11.5 second maintenance intervals. Task administration was computerized and participants' maximum span level was recorded at each maintenance interval. By measuring performance in terms of span at each maintenance interval, individual differences among participants can be controlled for (Logie et al, 1990).

6.4.2. Participants

A total of 56 participants (49 females; mean age = 20.73, standard deviation = 4.90 and 7 males; mean age = 26.29, standard deviation = 6.92) were randomly assigned to one of the three conditions (defined by task). Participants were all undergraduate psychology students at Northumbria University who had not participated in the previous studies and were paid in partial course credit.

6.4.3. Materials

Size Just Noticeable Difference (Size JND)

Procedure for the JND was the same as in Experiment 1 but with a variable maintenance interval (4.5, 8.5 or 11.5seconds). Participants completed a maximum of 20 trials at each level of difficulty (the difference between study and test stimuli decreasing across 5 difficulty levels: 40%, 30%, 20%, 10% and 5%), with criterion for progression being set at 15/20 (or a binomial probability of <.05) and maximum span level being taken as the last level successfully completed. Participants completed the task at all maintenance intervals and span level achieved was recorded.

High- and Low- Semantic Matrix Patterns Task

Participants completed a recognition version of both forms of matrix pattern task described in chapter 5. Entry level was 10 cells (measuring 10mm x10mm) with 5 filled this increased to a maximum of 30 with 15 filled. Participants completed a computerized version of this to ascertain their span level at each of the three maintenance intervals completing up to 20 trials at each level of difficulty, as in the JND criterion for progression being 15/20 (binomial $p < .05$) to counter the 0.5 probability for guessing.

For all tasks the stimuli were presented in an array measuring 160mm x 160mm and participants were seated to ensure a viewing distance of approximately 55cm.

6.4.4. Procedure

In all tasks, stimuli were presented for 1500msec followed by the variable maintenance interval and then the probe stimulus presented until response or timeout after 4000msec (see figure 6.1). Testing was blocked by maintenance interval and took place in one session lasting approximately 1 hour. Order of administration of the task at three different maintenance intervals was randomized for all participants and trials were randomized within each level.

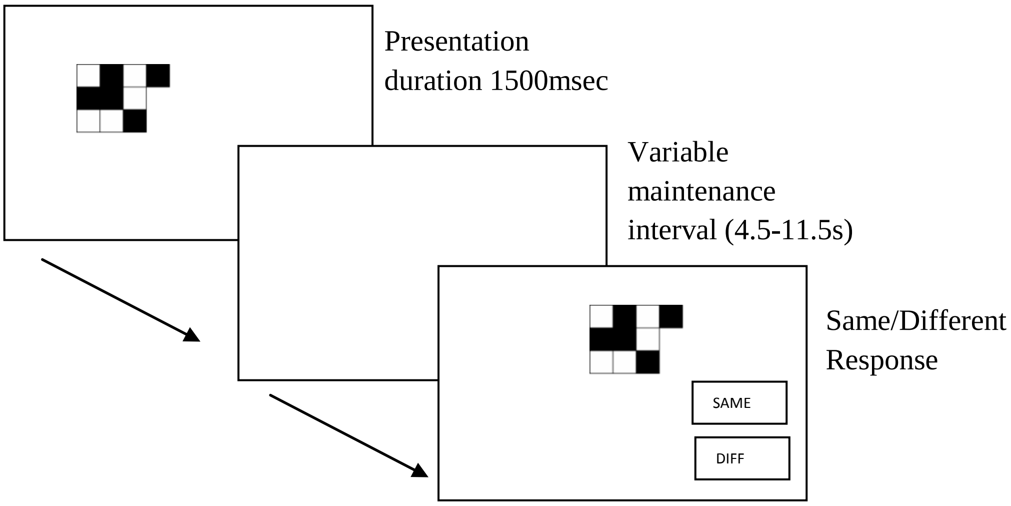


Figure 6.1. Protocol employed for the Recognition version of the Matrix Pattern Tasks

6.5. Experiment 2: Results

Table 6.1. Mean and Standard Deviations for span level on both forms of the matrix patterns task and smallest size difference reliably detected on the JND, across three maintenance intervals in a blocked design with a presentation time of 1500msec.

	JND (n=20)		Low Semantic (n=18)		High Semantic (n=18)	
	Mean	SD	Mean	SD	Mean	SD
4.5seconds	17.00	5.71	9.66	2.30	9.72	1.64
8.5seconds	23.00	8.01	7.94	1.98	9.50	1.58
11.5seconds	23.00	7.32	8.16	2.15	9.56	2.15

6.5.1. Analysis of Matrix Patterns

The two forms of matrix pattern task were analyzed in a 2 (High vs. Low Semantic) x 3 (Maintenance Interval) mixed ANOVA which revealed a significant main effect of maintenance interval ($F_{(2, 68)} = 7.007$; $p = .002$ $\eta_p^2 = .171$) with performance over 4.5seconds being significantly better than 8.5seconds ($p = .002$) and 11.5seconds ($p = .022$) but no difference between 8.5 and 11.5seconds ($p = 1.000$). There was no overall effect of the semantic manipulation ($F_{(2,68)} = 3.006$; $p = .092$), however there was a significant interaction effect ($F_{(2,68)} = 4.283$; $p = .018$ $\eta_p^2 = .112$). This will be investigated further in the following section analysing the effect of increasing maintenance interval.

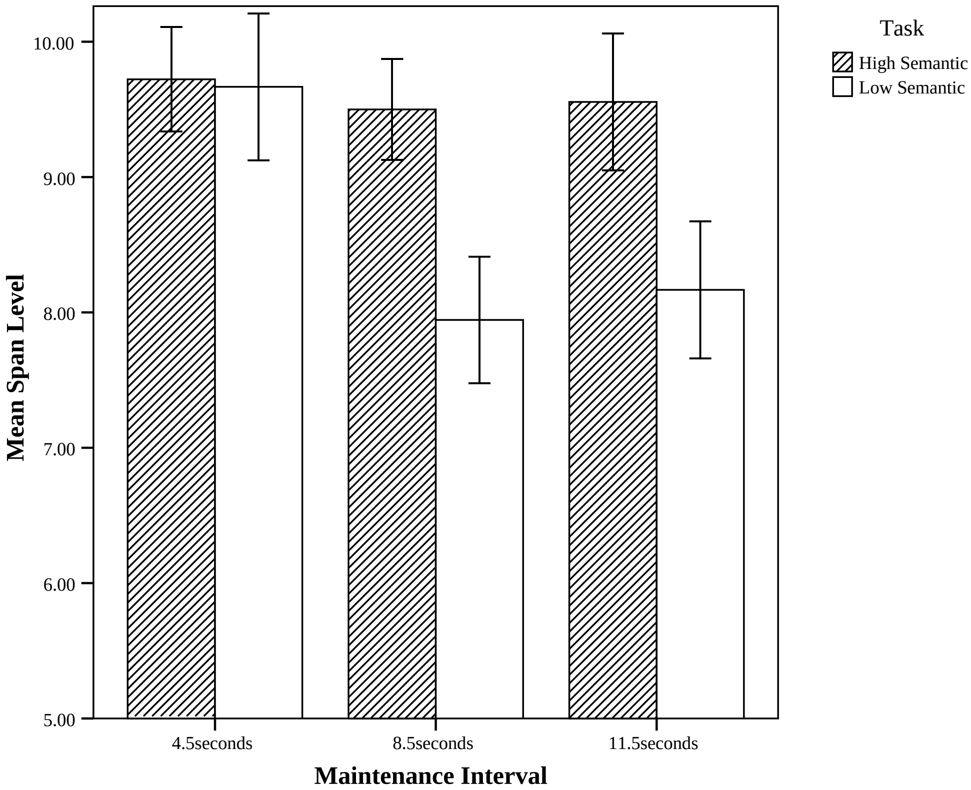


Figure 6.2. Mean span for high and low matrix pattern tasks across three maintenance intervals, with standard error bars (+/- 1 SE)

6.5.2. Analysis of Maintenance Interval

The effect of increasing maintenance interval was assessed using a one way repeated measures ANOVA for each task. Following Bonferroni correction there was a significant effect of maintenance interval for the low semantic matrix pattern task ($F_{(2,34)} = 14.752$, $p < .001$ $\eta_p^2 = .465$). Bonferroni Post Hoc comparisons revealed significantly better performance at 4.5s relative to the longer maintenance intervals (both $p < .001$) and no significant differences between the two longer maintenance intervals. The high semantic matrix pattern task showed no significant effect of maintenance interval, $F < 1$. As such the interaction seen between performances of the two variants of the matrix pattern task can be accounted for by the decrease in performance on the low semantic task across the three maintenance intervals which did not exist for the high semantic task. For the JND task there was a main effect of maintenance interval ($F_{(2,38)} = 5.104$, $p = .033$ $\eta_p^2 = .212$) with the pattern of performance being identical to the low semantic matrix patterns task. (When standardised, an analysis of the low semantic and the JND showed no significant interaction, $F < 1$).

6.5.3. Analysis of Z-Scores

To allow for comparison across the tasks participants span levels were standardized and a 3 (Task) x 3 (Maintenance Interval) mixed ANOVA conducted. This revealed a significant main effect of maintenance interval ($F_{(2,106)}$ = 10.050, $p < .001$ η_p^2 = .159). However, the interaction here failed to reach significance, $F_{(4,106)}$ = 1.616, p =.176.

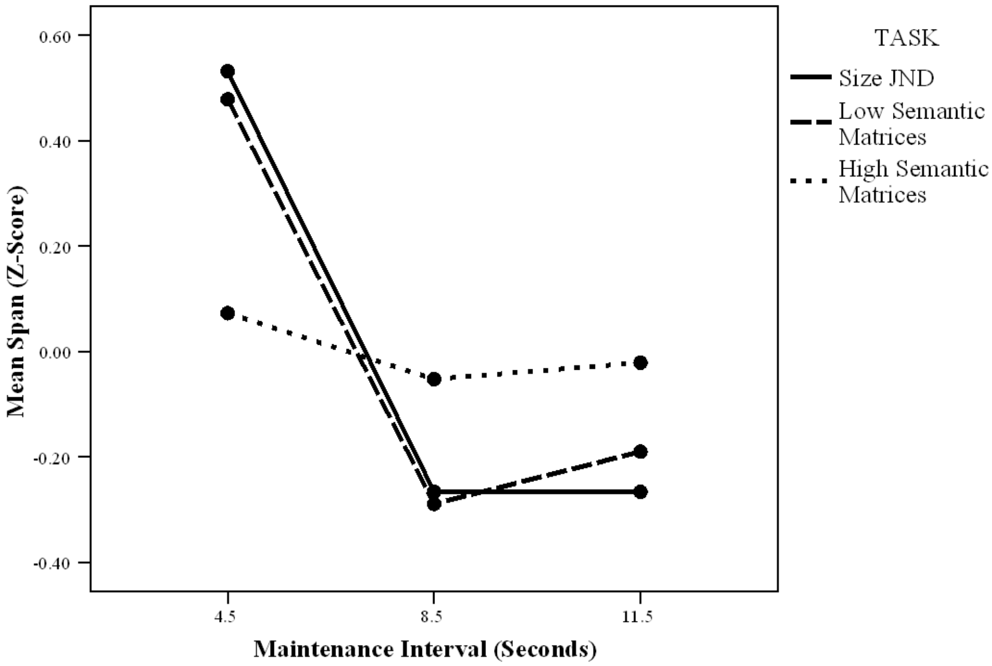


Figure 6.3. Graph Representing mean span (Z-score) for the JND and both forms of matrices at each of three maintenance intervals, in a blocked design (1500ms presentation time).

From Figure 6.3 It is clear that the performance of the low semantic matrix task is almost identical in nature to the Size JND suggesting that the reduction in the opportunity for semantic support lead to a reliance on the visual representation equivalent to that of the JND. In contrast to this, the high semantic matrix task showed no decay across the three maintenance intervals, this temporal profile is more in line with a task where the pattern configurations have the opportunity for categorical/semantic support (e.g. Andrade et al, 2002).

6.6. Experiment 2: Discussion

In this study, a set of visual matrix patterns, the low semantic set, was employed in order to reduce the opportunity for semantic support and categorical representation. It was predicted that this would compromise the quality of the categorical and low level visual binding and as a result the low semantic matrix representation would have reduced stability over increasing maintenance durations, akin to that seen in the Size JND. The pattern of results supported this prediction. In contrast, the high semantic set of matrix stimuli maintained their level of representation throughout the three maintenance intervals and produced a pattern of temporal stability commensurate with that found by Andrade et al (2002). A more detailed discussion of these results will follow experiment 4.

6.7. Experiment 3: Maintenance in a Randomised Design

One concern in using blocked designs with matrix patterns was raised by Kerr, Ward and Avons (1998). They propose that using a blocked design may enable a participant to employ a different strategy depending on the length of time over which they have to maintain the patterns, as the maintenance duration is predictable. As such the following experiment was conducted to replicate the findings of the previous study using a randomized design, in which participants couldn't predict the duration of the maintenance interval.

6.8. Experiment 3: Methods

6.8.1. Participants

A total of 48 participants took part in the experiment (41 females; Mean Age = 19.37, standard deviation = 3.82 and 7 males; mean age = 21.86, standard deviation = 8.90) who were all undergraduate students at the University of Northumbria and had not participated in any of the previous experiments. Participants were recruited via advertisements placed in the psychology department and were paid in partial course credit.

6.8.2. Design and materials

The design was the same as that used in the previous study; however a randomized rather than a blocked design was used. As such each participant completed 60 trials at each level of complexity, 20 of which had a maintenance interval of 4.5seconds, 20 had a maintenance interval of 8.5seconds and 20 a maintenance interval of 11.5seconds. The trials were randomized within each level and criterion for progression was 15/20 (binomial $p < .05$) to counter the 0.5 probability of guessing.

6.8.3. Procedure

Presentation time for each stimulus remained the same as in the previous study. Testing took place in one session lasting approximately 1hour. Every 20 trials participants were given a break and instructed to continue when ready.

6.9. Experiment 3: Results

Table 6.2. Mean and Standard Deviations for span level on both forms of the matrix patterns task and smallest size difference reliably detected on the JND, across three maintenance intervals in a randomised design.

	JND (n = 16)		Low Semantic (n = 16)		High Semantic (n = 16)	
	Mean	SD	Mean	SD	Mean	SD
4.5seconds	18.31	5.96	8.20	1.56	8.00	1.70
8.5seconds	22.95	9.61	7.24	1.24	8.16	1.35
11.5seconds	26.68	10.21	7.13	1.44	8.03	1.70

6.9.1. Analysis of Matrix Patterns

Analysis of the two forms of matrix pattern task in a 2 (High vs Low Semantic) x 3(Maintenance Interval) mixed ANOVA revealed a significant main effect of maintenance interval ($F_{(2, 60)} = 8.862$; $p < .001$ $\eta_p^2 = .228$) with performance over 4.5seconds being significantly better than 8.5seconds ($p = .021$) and 11.5seconds ($p = .002$) but no difference between 8.5 and 11.5seconds ($p = .815$). As seen in the previous study there was no overall effect of the semantic manipulation ($F_{(1, 30)} = 1.407$; $p = .241$), however there was a significant interaction effect ($F_{(2, 60)} = 3.303$; $p < .001$ $\eta_p^2 = .296$).

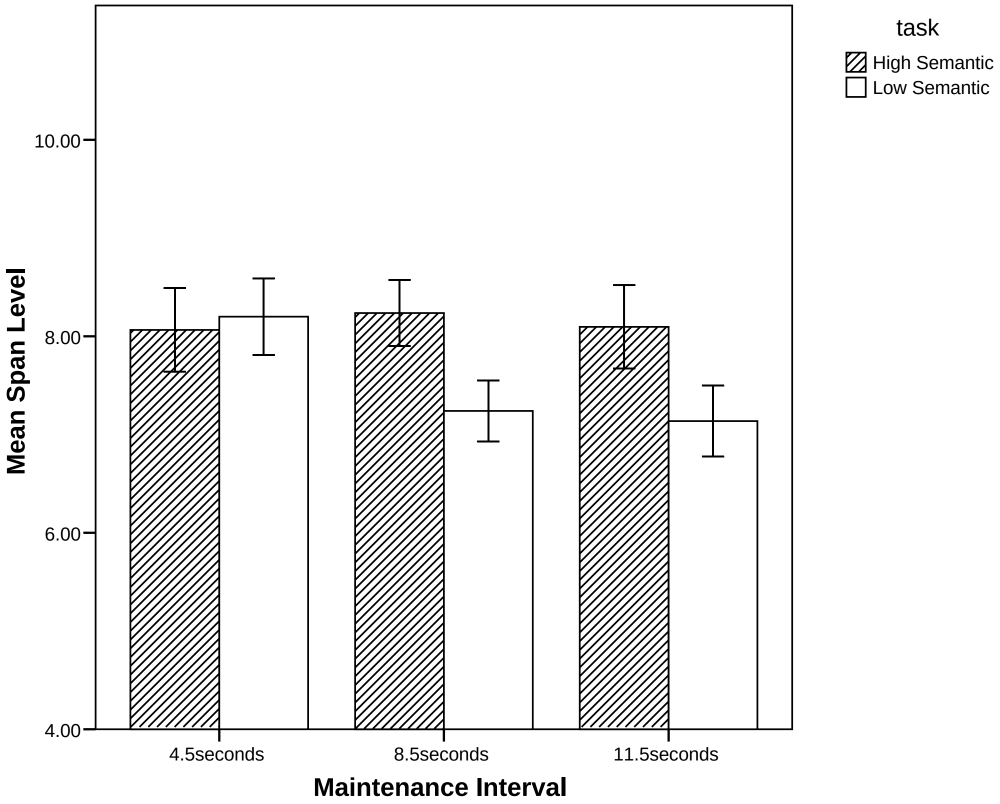


Figure 6.4. Mean span in a randomised procedure for high and low matrix pattern tasks across three maintenance intervals, with standard error bars (+/- 1 SE)

6.9.2. The Effects of Maintenance Interval

The effect of increasing maintenance interval was assessed using a one way repeated measures ANOVA for each task. Following Bonferroni correction there was a significant effect of maintenance interval for the low semantic matrix pattern task, $F_{(2,\ 30)} = 17.124$, $p <.001$ $\eta_p^2=.553$. Post Hoc comparisons revealed significantly better performance at 4.5s relative to the longer maintenance intervals ($p < .001$) and no significant differences between the two longer maintenance intervals ($p = 1.000$). The high semantic matrix pattern task showed no significant effect of maintenance interval, $F < 1$. For the JND task there was a main effect of maintenance interval ($F_{(2,\ 30)} = 7.627$, $p = .002$ $\eta_p^2 = .337$) with performance at 4.5seconds being significantly better than 11.5seconds ($p = .007$) but not different from 8.5seconds ($p = .071$) and no difference between the two longer maintenance intervals ($p = 1.000$).

6.9.3. Analysis of Z-Scores

To allow for comparison across the tasks participants span levels were standardized and a 3 (Task) x 3 (Maintenance Interval) repeated measured ANOVA conducted. This revealed a significant main effect of maintenance interval ($F_{(2, 90)} = 16.026$, $p < .001$ $\eta_p^2 = .263$). In contrast to the previous study the interaction also reached significance, $F_{(4, 90)} = 5.281$, $p = .001$ $\eta_p^2 = .190$.

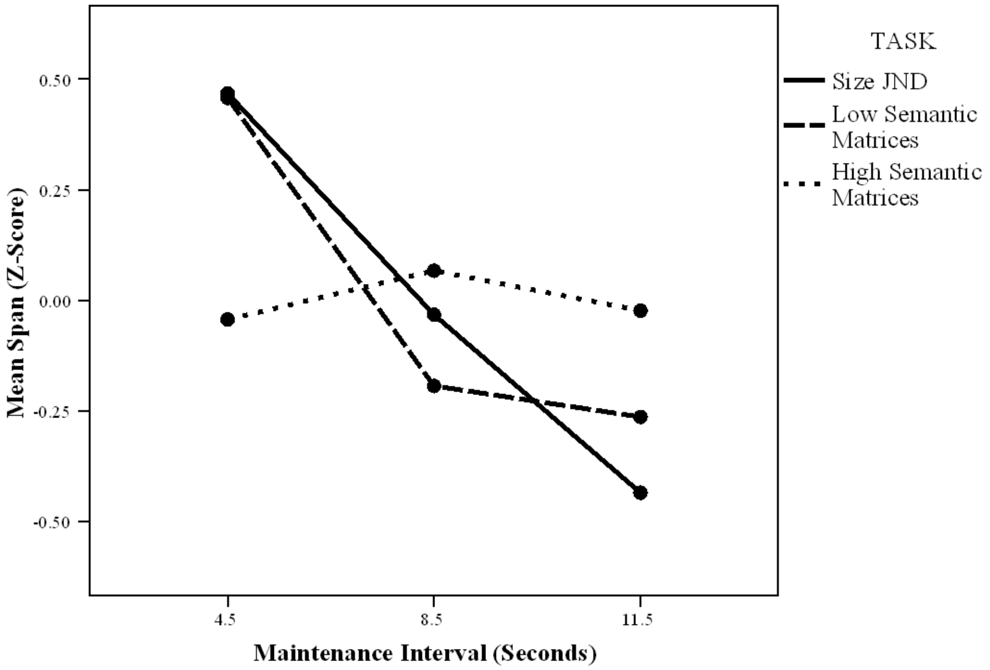


Figure 6.5. Graph Representing mean span (Z-score) for the JND and both forms of matrices at each of three maintenance intervals, in a randomised design (1500ms presentation time).

6.9.4. Comparisons with Experiment 2

Size JND. Comparison across studies 2 and 3 shows no difference on the JND task between blocked and randomised designs respectively across all maintenance intervals ($F_{(1,34)} =.718$, $p = .403$) and no interaction between design and maintenance interval ($F_{(2, 68)} =.716$, $p = .478$).

Low Semantic Matrices. There was no significant difference between randomised and blocked designs ($F_{(1,32)} = 3.299$, $p = .079$) and no interaction ($F_{(2,64)} = 1.726$, $p=.186$), suggesting an identical pattern of performance.

High Semantic Matrices. Finally for the high semantic matrix patterns task there was a difference in performance between the two studies ($F_{(1, 32)} = 8.083$, $p = .008$ $\eta_p^2 = .202$) but no interaction effect ($F_{(2, 64)} = .318$, $p = .729$). Suggesting a drop in performance in the randomised design relative to the blocked, but no change in decay function.

6.10. Experiment 3: Discussion

Overall these results appear to replicate those of experiment 2 with the exception of the high semantic task, which showed a decrement in overall performance (the low semantic also showed a tendency towards a difference). This may be due to fatigue/motivation effects, as in the randomized version of the tasks (mean span level = 8.13) participants complete one task over the course of 1 hour with difficulty level increasing until maximum span is achieved whereas in the blocked version (mean span level = 9.59) participants complete three separate tasks across the hour testing session, perhaps reducing fatigue. The lack of an interaction effect shows that change (or lack thereof) in performance across the maintenance intervals is equivalent in both the randomized and the blocked versions of the task.

In contrast to research reported by Kerr et al (1998) these results suggest that participants are not employing different strategies for patterns which need to be maintained over different maintenance intervals. The present results also support the findings in experiment 2 which suggest that performance on the low semantic matrix task across the range of maintenance intervals, is more similar in nature to the Size JND than it is to the high semantic task and that this is not a function of the experimental paradigm employed.

6.11. Experiment 4: The Time Course of Semantic Elaboration

Ichikawa (1985) showed that both quantitative and structural factors contribute to memory for matrices. However, the contribution of structural factors (factors involving high level cognition) was shown to increase across presentation durations. The two forms of matrix pattern employed in the present thesis were designed to be differentially dependent on high level semantic representation.

To provide further support for the hypothesis that performance on the high semantic task is supported and facilitated by categorical representation the following study reduced the encoding time of the stimuli. Cowan et al (1990) propose that building up a semantic representation of a stimulus takes both attention and time, as such by limiting the amount of time available, the amount of semantic elaboration will also be limited (Stevanoski & Jolicoeur, 2007) leaving participants more reliant on the low level pre-categorical representation similar to that of the low semantic patterns task and the Size JND in the previous two studies.

6.12. Experiment 4: Method

6.12.1. Participants

A total of 48 participants took part (42 females; mean age = 19.90, standard deviation = 6.70 and 6 males; mean age = 19.33, standard deviation = 1.86). These were all undergraduate psychology students at Northumbria University paid in partial course credit. The participants in the present study had not taken part in the previous studies.

6.12.2. Design, Materials and Procedure

A mixed design was used in which task was a between subjects variable and maintenance interval was within-subjects. Task administration was computerized and participants' maximum span level was recorded at each maintenance interval. The procedure and materials used in this experiment were the same as those in Experiment 2, the only difference being that presentation time was reduced from 1500msec to 500msec for each stimulus.

6.13. Experiment 4: Results

Table 6.3. Mean and Standard Deviations for span level on both forms of the matrix patterns task and smallest size difference reliably detected on the JND, across three maintenance intervals in a blocked design, with a presentation time of 500msec.

	JND (n = 16)		Low Semantic (n = 16)		High Semantic (n = 16)	
	Mean	SD	Mean	SD	Mean	SD
4.5seconds	18.75	3.42	8.00	1.71	8.88	1.82
8.5seconds	22.50	9.31	6.63	1.75	7.50	1.83
11.5seconds	24.38	8.14	6.31	1.85	7.31	2.12

6.13.1. Analysis of Matrix Patterns

Analysis of the two forms of matrix pattern task in a 2 (Level of Semantics) x 3 (Maintenance Interval) mixed ANOVA revealed a significant main effect of maintenance interval ($F_{(2, 60)} = 16.657$; $p < .001$ $\eta_p^2 = .357$) with performance over 4.5seconds being significantly better than 8.5seconds ($p = .021$) and 11.5seconds ($p = .002$) but no difference between 8.5 and 11.5seconds ($p = .815$). There was no overall effect of the semantic manipulation ($F_{(1, 30)} = 2.748$; $p = .108$ $\eta_p^2 = .084$), and in contrast to the previous studies there was no significant interaction effect ($F < 1$).

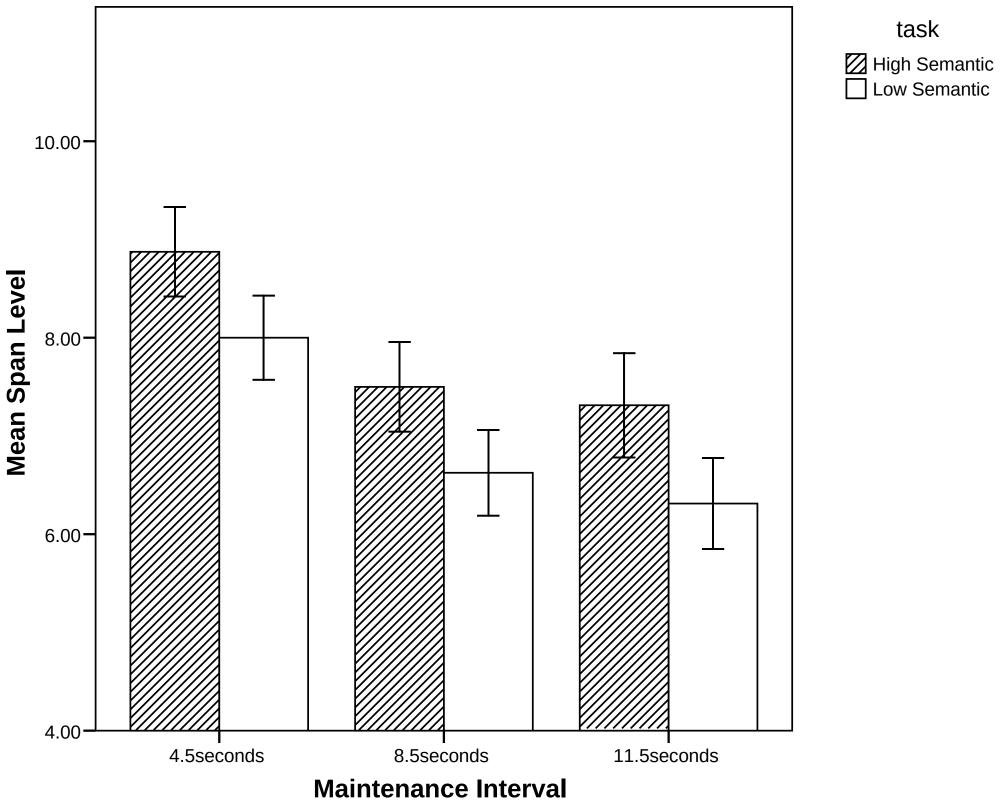


Figure 6.6. Mean span in a blocked procedure (p.t. 500 msec) for high and low matrix pattern tasks across three maintenance intervals, with standard error bars (+/- 1 SE).

6.13.2. Analysis of Maintenance Interval

The effect of increasing maintenance interval was assessed using a one way repeated measures ANOVA for each task. Following Bonferroni correction there was a significant effect of maintenance interval for the low semantic matrix pattern task, $F_{(2, 30)} = 10.685$, $p < .001$ $\eta_p^2 = .416$. Bonferroni Post Hoc comparisons revealed significantly better performance at 4.5s relative to the longer maintenance intervals ($p < .010$) and no significant differences between the two longer maintenance intervals ($p = .937$), an identical pattern of results as seen in the previous two experiments. However, in contrast to the previous two studies the high semantic matrix pattern task showed a significant main effect of maintenance interval, $F_{(2, 30)} = 6.713$, $p = .004$ $\eta_p^2 = .309$, post hoc comparisons revealed performance at 4.5s was significantly better than 11.5s ($p = .003$) but did not differ from 8.5s ($p = .053$) and that there was no difference between 8.5 and 11.5s ($p = 1.000$). For the JND task the main effect of maintenance interval failed to reach significance ($F_{(2, 30)} = 2.455$, $p =.103$ $\eta_p^2 = .141$).

6.13.3. Analysis of Z Scores

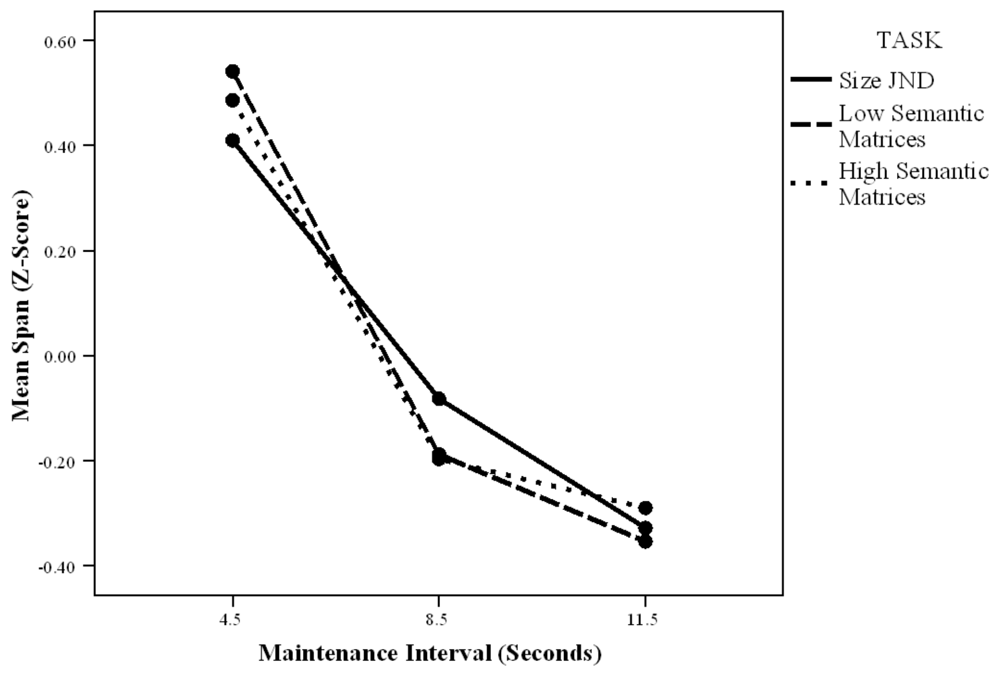


Figure 6.7. Graph Representing mean span (Z-score) for the JND and both forms of matrices at each of three maintenance intervals, in a blocked design (500ms presentation time).

To allow for comparison across the tasks participants span levels were standardized and a 3 (Task) x 3 (Maintenance Interval) repeated measured ANOVA conducted. This revealed a significant main effect of maintenance interval ($F_{(2, 90)} = 15.303$, $p < .001$ $\eta_p^2 = .254$) and importantly no significant interaction, $F < 1$. Figure 6.7 shows that when presentation time is reduced (and therefore the opportunity for semantic elaboration is denied) the decay in performance across the three maintenance intervals is equivalent for all tasks.

6.13.4. Comparison with Experiment 2

Size JND. Although the effect of maintenance interval for the Size JND failed to reach significance in the present study, comparison between experiments 2 and 4 shows no difference on the JND task in overall performance ($F < 1$) and no interaction ($F < 1$).

Low Semantic Matrices. There was a difference across the studies in terms of overall span level achieved ($F_{(1, 32)} = 6.963$, $p = .013$ $\eta_p^2 = .179$), with average span level using a 1500msec presentation time being 8.59 and with a 500msec presentation time it was 6.70. However, there was no significant interaction ($F_{(2, 64)} = .550$, $p = .580$) suggesting the overall pattern of decay across the three maintenance intervals was unaffected by the decrease in presentation time.

High Semantic Matrices. There was a significant difference in performance between the two studies, ($F_{(1, 32)} = 10.569$, $p= .003$ $\eta_p^2 = .248$); mean span level at 1500msec (9.60) was significantly higher than at 500msec (7.90). The interaction failed to reach significance ($F_{(2,64)} = 2.686$,$p = .076$), however as discussed above, even following Bonferroni corrections with a 500msec presentation time participants' span level dropped significantly with an increase in maintenance intervals and this effect was not present in the 1500msec presentation time condition.

An analysis of the low semantic patterns task with a 1500msec presentation time compared to the high semantic pattern task with a 500msec presentation time showed no significant differences in either mean span level ($F_{(1,32)}$=1.257, p=.271) or the effect of maintenance interval ($F < 1$).

6.14. Experiment 4: Discussion

These results support the idea that performance on the high semantic matrix patterns task is scaffolded by semantic elaboration of the representation. However, this semantic elaboration process takes time (e.g. Curby & Gauthier, 2007) and when this is denied by a reduction in presentation time, performance is more akin to that of the low semantic matrix patterns task than the high semantic with a longer encoding duration.

Interestingly performance on the JND was unaffected by the reduction in encoding time but the low semantic patterns task was significantly impaired. This suggests that although performance on the low semantic task is more equivalent to the JND than the high semantic task at 1500msec encoding time, it may still be benefiting from some sort of semantic or categorical encoding, though this is not sufficient to prevent decay of performance across increasing maintenance intervals.

6.15. General Discussion

The general results of the studies in the present chapter have demonstrated that when there is sufficient encoding time for semantic elaboration of the stimulus, the matrix patterns which lend themselves more readily to semantic representation can be maintained over 11.5seconds without significant decay. When the opportunity for semantic elaboration is denied, either by reducing encoding time (experiment 4) or by changing the structure of the stimulus (experiments 2 and 3), there is decay in performance akin to that of the Size JND which is employed as a benchmark for visual STM representation.

A first point of discussion here is that this could be responsible for the inconsistency in the literature concerning matrix patterns. As discussed in chapters 4, 5 and in the present chapter, several studies have employed matrices and shown no decay over relatively long maintenance intervals (e.g. 36seconds; Andrade et al, 2002). There have also been studies showing a link with central executive resources (e.g. Thompson et al, 2006). In contrast to this, other studies have shown performance in matrix pattern tasks more typical of visual STM (e.g. Phillips, 1974) and no links with executive resources (e.g. Rudkin et al, 2007). The present study demonstrates that this could be due to variance across stimulus sets; it is possible that the matrices employed in some studies may lend themselves more readily towards semantic support than those used in other studies.

The second theoretical issue for discussion is that of semantic elaboration in visual working memory. Luck (2009) propose that VSTM representations are perceptual representations created from sensory input that have stabilized and remained active after the offset of sensory input; Vogel, Woodman & Luck (2006) investigated colour change detection with presentation of a mask at a variable interval after the sample array, proposing that if any time is needed to convert perceptual information into VSTM information after stimulus offset then the masks should cause interference. The effect of masking was much larger and persisted for longer after the offset of the sample array as set size increased, suggesting that more time is needed to create VSTM representations as more items are presented in an array. The authors went on to suggest that each items-worth of information to be encoded takes roughly 50msec. However, this is limited to the bottom-up processing of simple colour stimuli and may differ with complex stimuli.

Curby and Gauthier (2007) demonstrated an advantage for upright over inverted faces but only when participants were given sufficient encoding time (i.e. 1500msec or greater) and that at a 2500msec encoding duration, capacity for faces approximates capacity for other object categories (e.g. cars). However, they showed that capacity for upright faces exceeded that of other object categories at 4500msec maintenance interval; suggesting that, for complex stimuli, semantic elaboration can continue long beyond that proposed by Vogel et al (2006) and for face-arrays, may continue over at least 4500msec.

In Cowan's (2005) embedded processes model, discussed in Chapter 2, when a stimulus is attended to in STM, more of the features associated with the stimulus in LTM are activated and as such a more stable memory representation is formed. In the verbal domain, Cowan et al (1990) demonstrated enhanced encoding through the production of longer-lasting categorical representations instead of simpler acoustic representations. They also provided evidence that shifting attention towards the stimulus can help to create these longer-lasting memory representations. This lends itself towards a model in which the opportunity for elaboration in complex stimuli exists beyond the 50msec suggested by Vogel et al (2006) for simple items.

Although employed as a benchmark for visual STM performance, the Size JND has provided data which have interesting theoretical implications. Cowan (1992) proposes that passing an object through, or keeping it in, the focus of attention should keep the representation in an active state. However, in the present study participants were able to pay full attention to the task and the Size JND representation still showed significant decay. This suggests that the resolution of representations in working memory can perhaps be lost across increasing maintenance intervals. This concept will be discussed at length in chapter 9.

In terms of the data presented in this chapter, it appears that the high-semantic patterns benefit, both in terms of absolute performance and in terms of the stability of the maintained representation when encoding duration is increased from 500msec to 1500msec. This semantic elaboration of the stimuli, lends support for the embedded processes model, whereby the elaboration is gradual and effortful but leads to a more stable representation. It may be the process of consciously attending to the stimulus to allow for elaboration that involves central executive processes.

Chapter 4 showed extensive involvement of executive resources in performance on the matrix pattern task. The suggestion arising from the present chapter is that this executive involvement is, at least in part, due to the integration and maintenance of dual-representations of the matrices. matrix patterns appear to be represented in both categorical and pre-categorical form. This is consistent with the suggestions made by Chipman (1977) and Ichikawa (1985) where patterns consist of quantitative and structural factors, or Avons and Phillips (1987) suggestion of visuospatial and semantic descriptions of patterns. The following chapter (Chapter 7) will aim to demonstrate a differentiation in executive involvement across the two sets of matrices by creating both 2-back and 1-back versions of the task. Chapter 8 will then go on to characterise the processes involved in the maintenance of the two forms of task and the Size JND in a dual-task paradigm.

6.16. Chapter Overview

The present chapter has served to characterize the temporal profile of the maintenance of the Size JND which was then used as a benchmark for VSTM performance and compared to both high and low semantic visual matrices. It was demonstrated in Experiment 2 (and replicated in experiment 3), that low semantic matrices have a temporal profile akin the Size JND but that high semantic matrices show no decay over an unfilled interval of up to 11.5seconds. Experiment 4 demonstrated that the stability of the maintained high semantic representation could be compromised by reducing encoding duration from 1500msec to 500msec, suggesting that the semantic elaboration processes afforded by high semantic patterns persists beyond the first 500msec of the stimulus presentation.

CHAPTER 7

Representation of Visual Patterns in Short and Long Term Visual Memory

7.1. Chapter Overview

Experiment 1 demonstrated extensive executive involvement in performance of a visual matrix task. One possible source of executive involvement is the formation of multiple representations of the visual patterns in working memory, specifically the integration of semantic support for the visual short term memory representation. In chapter 5 two sets of matrix pattern were created, one which lends itself readily to semantic support and one which does so to a lesser extent.

In Experiments 2, 3 and 4 the temporal characteristics of these pattern sets were identified, specifically the stability of the representations across increasing maintenance intervals, and the effect of limiting encoding time. It was demonstrated that the low semantic matrices showed a decay function akin to that of the Size JND, employed as a benchmark for visual STM. In contrast, the high semantic matrices showed no decay in performance across increasing maintenance intervals. When encoding time was reduced, performance on the high semantic matrices showed a decay function akin to low semantic matrices and the Size JND, suggesting the semantic elaboration of the pattern is a time dependent process.

The present chapter is concerned with the impact of executive interference and the contribution of categorical processing to the two pattern sets relative to each other and relative to the Size JND task, used throughout the thesis as a benchmark for pre-categorical short-term memory representations.

7.2. Background

As discussed in chapter 1, Phillips and Christie (1977a; 1977b) demonstrated a serial position curve for visual patterns, with a clear one-item recency effect and above chance recognition performance on pre-recency patterns. There is substantial evidence that visual memory for patterns or static memory for sequences consists of distinct short-term and long-term components (e.g. Kemps, 1999; Kroll, 1975; Phillips & Christie, 1977a; 1977b; Posner et al, 1969; Rossi-Arnaud et al, 2006). Research employing matrix patterns has shown the short term component to have a limited capacity (Phillips, 1974) and is particularly sensitive to the presentation of a subsequent visual stimulus, to the point that it appears to hold a single item which is presumed to be the cause of the characteristic one-item recency effect observed in serial order memory for matrices (Phillips & Christie, 1977a). It also appears that the short term component involves active maintenance (perhaps executively driven), since decay time is variable and the recency effect is removed by interference tasks, such as mental arithmetic, which is modality-independent but has a high mental load (Phillips & Christie, 1977b). The long term component of visual memory is that which survives interference from subsequent visualisation or secondary tasks and can retain an indefinite number of items. In addition, the short term component increases much more rapidly as a function of display time than the long-term component (Avons & Phillips, 1980); this is similar to the effect seen in Experiment 4 where the encoding of semantic features is a much slower process.

Broadbent and Broadbent (1981) argue that the matrix patterns used by Phillips and Christie contained familiar shapes which afford LTM semantic support, proposing this to be the source of the above chance level of performance on pre-recency items. Further to this, Avons and Phillips (1987) have demonstrated that the semantic representation of familiar forms within matrix patterns can make a significant contribution to memory for pre-recency items. However, Walker et al (1993) replicated the serial position curve for visual matrices when presenting a sequence of visual patterns in a random spatio-temporal order requiring participants to remember the location of the probed pattern. In a further experiment they demonstrated that in the serial position curve, visual similarity had a detrimental effect on both the recency and the pre-recency items, suggesting both rely on a visual representation.

Research presented in chapter 5 discusses the substantial body of evidence supporting the use of multiple levels of representation in matrix pattern tasks. Avons and Phillips (1987) propose two levels of description in matrix patterns, the first of which they term *visuospatial description.* Such descriptions are concerned with visual appearance and spatial relationships between ‘units’ in a pattern, however, the authors point out that this type of description may also make use of higher level configurations such as visual semantics. This involves the semantic representations being accommodated into the input of the pattern by making modifications to the internal representation. Building a visuospatial description using higher-level representations was hypothesised to increase the capacity for patterns, perhaps by increasing the amount of information contained within one ‘chunk’ (e.g. Cowan et al, 2004). The second level of description is *semantic description,* this involves description of the matrix in the absence of visuospatial description. For example, familiar forms within the pattern may be recognised and remain activated until tested but information regarding spatial relations of the elements or modifications to the internal representations may be lost. In which case, recognition performance relies solely on the patterns categorical representations.

It is proposed by Avons and Phillips (1987) that in the serial position curve observed for matrices, the recency item is supported by a visuospatial description, whereas the pre-recency items are described semantically. As visuospatial description contains both low-level visual description and the integration of high-level familiar forms, subsequent visual stimuli lead to interference with the visuospatial description and lead to the characteristic pre-recency performance. However, research presented above by Walker et al (1993) clearly demonstrates the involvement of visual description in pre-recency performance; it therefore seems plausible that the two components of the serial position curve involve the both forms of description with difference emphases or reliance placed on them.

The first aim of the present chapter therefore, is to employ the high and low semantic sets created in chapter 5 in a paradigm which will force participants to represent the patterns in the pre-recency or long-term component of visual memory. This will be achieved by implementing a 2-back procedure, in which participants’ task is to recognise whether the pattern they are looking at is the same or different as one presented two beforehand. The introduction of an intervening visual pattern should ensure that participants are unable to maintain the patterns in a recency format. If pre-recency items are represented by semantic description, then the low semantic patterns should lead to lower levels of performance than the high semantic patterns as they afford less semantic description.

A further point of interest in the present chapter is concerned with the nature of forming multiple levels of representation of the matrix patterns. If, as suggested above, the patterns are represented at a visuospatial and a semantic level then this by its very nature should implicate the involvement of the episodic buffer (Baddeley, 2000). The nature of the binding of multiple representations into a single episode was discussed in chapter 3. It was initially hypothesised by both Cowan (2005) and Baddeley (2000) that this process should be demanding of executive resources. However, research looking at the binding of low-level features of a visual stimulus such as colour and shape or symmetry has failed to show the involvement of executive resources (e.g. Allen et al, 2006; Allen et al 2009; Rossi-Arnaud et al, 2006). Research employing memory for prose, which is known to involve the integration of phonological and long-term representations (Baddeley, 2007), has also produced inconclusive results regarding the executive demands placed by binding (e.g. Baddeley et al, 2009; Chalfronte & Johnson, 1996; Jeffries et al, 2004; Naveh-Benjamin et al, 2004). However, research investigating the integration of short-term and long-term information in the visual domain is lacking.

Jeffries et al (2004) and Rudner and Ronnberg (2008) propose that when slave system capacity is exceeded (as it is in a span task), central executive resources are recruited to chunk parts of the stimulus and reduce information load. In the present study access to the central executive will be compromised by the n-back procedure. As such it is predicted that this will limit the opportunity for chunking and therefore leave participants reliant on slave system capacity.

7.3. Experiment 5: 2-back procedure

The present study aims to increase the executive demands placed on both forms of matrix task to observe their reliance on executive resources. This will be achieved in two ways. Firstly, the two forms of matrix pattern will be employed in a 2-back procedure. This will serve to make participants rely on the pre-recency representation of the visual patterns. It will also make sufficient executive demands to observe the impact of executive interference on these representations. However, as this is confounded by the impact of an intervening stimulus, the second experiment in the series employs the matrices in a 1-back, allowing for the assessment of executive interference in the absence of visual interference. Therefore, the second experiment is concerned with the executive interference on the short-term or recency component of matrix pattern representation. In both experiments, the size JND will be employed in the same way as a benchmark for pre-categorical short term representation.

7.4. Experiment 5: Methods

7.4.1. Participants

A total of 57 participants took part (53 females; mean age = 22.46, standard deviation = 7.07 and 14 males; mean age = 24.50, standard deviation = 3.54), these were all psychology students at Northumbria University paid in partial course credit. Participants were excluded if they had taken part in any of the previous studies.

7.4.2. Design

A mixed design was used in which the visual memory task was a between subjects factor with three levels, Size JND, low semantic Matrices and high semantic Matrices. Maintenance interval was a within subjects factor with three levels, 4.5, 8.5 and 11.5 seconds maintenance intervals. This maintenance interval refers to the interval between the onset of the present stimulus (n) and the offset of n-2, matching the maintenance intervals used in the previous studies (see figure 7.1). Task administration was computerized and participants' maximum span level was recorded at each maintenance interval.

7.4.3. Materials and Procedure

The methodology used in the previous chapter was adapted in the present study to examine the costs of a concurrent executive load. The advantage of considering these effects in the n-back paradigm is that it minimises potential trade off effects. In the traditional dual-task paradigm, a response is given to both the primary and secondary tasks and therefore dual task costs may arise because of response competition. In the n-back procedure, integrating the secondary task (updating of material in memory) into the primary (memory for the stimulus) only results in one response being required, making the interpretation of the data less problematic.

Size Just Noticeable Difference (Size JND)

Participants completed a 2-back recognition version of the JND, with a maximum of 20 test trials at each level of difficulty (the difference between study and test stimuli decreasing across 5 difficulty levels: 40%, 30%, 20%, 10% and 5%), with criterion for progression being set at 15/20 (or a binomial probability of <.05) and maximum span level being taken as the last level successfully completed. Participants completed the task at all maintenance intervals and span level achieved was recorded.

High- and Low- Semantic Matrix Patterns Task

Participants completed a 2-back recognition version of both forms of the matrix pattern task described in chapter 5. Entry level was 10 cells (measuring 10mm x10mm) with 5 filled, this increased to a maximum of 30 with 15 filled. Participants completed a computerized version of this to ascertain their span level at each of the three maintenance intervals completing up to 20 trials at each level of difficulty, as in the JND criterion for progression being 15/20 (binomial $p < .05$) to counter the 0.5 probability for guessing.

7.4.4. General Procedure

Participants were given standard instructions (see appendix E and F), the stimuli (square or pattern) were presented for 1500msec one after another, with an inter stimulus interval of 1.5, 3.5 or 5seconds. The stimuli were presented on the screen such that two consecutive patterns were never presented in the same location. Participants were instructed to respond on each trial to indicate whether the stimulus on the screen was the same or different to one presented two beforehand (as described in figure 7.1). They progressed through the levels of difficulty until performance fell below the criterion for progression, at which point the program terminated and participant moved on to the next condition (conditions were blocked by maintenance interval).

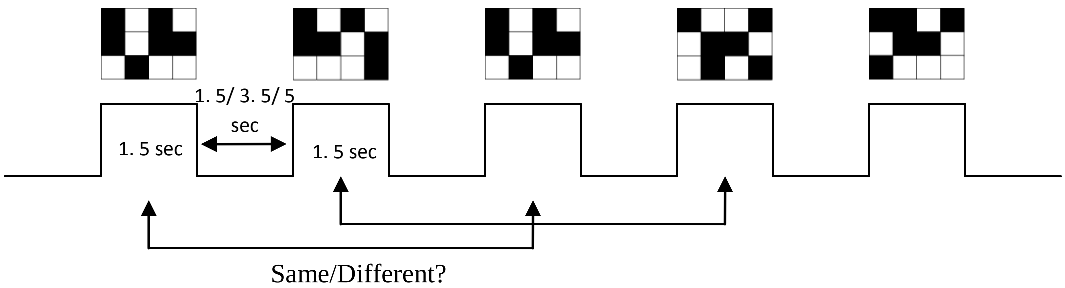


Figure 7.1. Protocol employed in the 2-back task

As shown above in figure 7.1. Inter-stimulus intervals of 1.5, 3.5 and 5 seconds were chosen to equate the maintenance interval between study and test stimuli to those used in the previous chapter (4.5, 8.5 and 11.5 seconds). Further to this null trials were included so that the same stimulus wasn't tested in both same and different trials and that in 'different' trails the stimulus only differed by one cell.

For all tasks the stimuli were presented in an array measuring 160mm x 160mm and participants were seated to ensure a viewing distance of approximately 55cm.

7.5. Experiment 5: Results

For the high semantic task, 6 participants were excluded as they did not successfully pass entry level of the task at all three maintenance interval. The same was true for 2 participants in the JND task. For the low semantic task, no participants completed entry level (level 4) at *any* of the three maintenance intervals.

Table 7.1. Mean and Standard deviation for span level for the three 2-back tasks over three maintenance intervals.

	JND (n = 14)		Low Semantic (n = 0)		High Semantic (n = 16)	
	Mean	SD	Mean	SD	Mean	SD
4.5seconds	31.33	9.15	--	--	5.56	0.89
8.5seconds	36.00	6.32	--	--	4.94	0.77
11.5seconds	38.00	4.14	--	--	4.88	0.50

7.5.1. Analysis of Matrix Patterns

No participants in the low semantic matrix task successfully completed entry level (which was reduced to level 4 in the present study), as such no comparison can be drawn between performance on the two forms of matrix task.

7.5.2. Analysis of Maintenance Interval

To investigate the effect of increasing maintenance interval, one way repeated measures ANOVAs were conducted for each task.

Size JND

Following Bonferroni correction there was a significant effect of maintenance interval for the JND, $F_{(2,\ 28)} = 6.870$, $p = .004$ $\eta_p^2 = .329$. Bonferroni Post Hoc comparisons revealed significantly better performance at 4.5s relative to 11.5seconds ($p = .003$), no significant differences between the 4.5seconds and 8.5seconds ($p = .144$) or 8.5seconds and 11.5seconds ($p=.813$).

High Semantic Matrices

The high semantic matrix pattern task showed a significant main effect of maintenance interval, $F_{(2,\ 30)} = 8.627$, $p = .001$ $\eta_p^2 = .365$, post hoc comparisons revealed performance at 4.5s was significantly better than 8.5s ($p=.001$) and 11.5s ($p = .002$) but 8.5s did not differ from 11.5s ($p = 1.000$).

7.5.3. Analysis of Z Scores

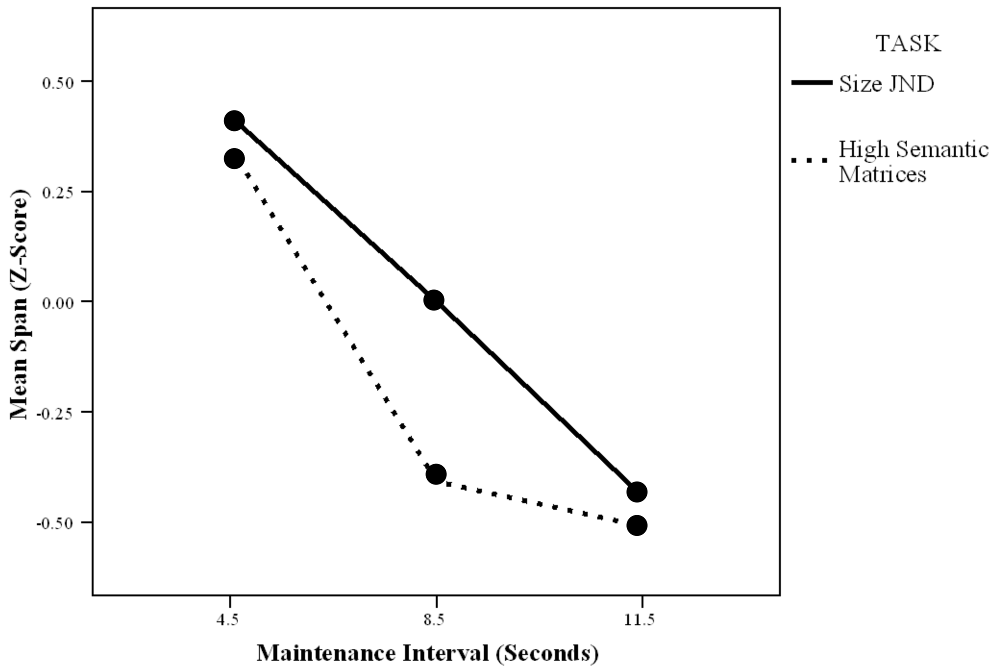


Figure 7.2. Graph Representing mean span (Z-score) for the JND and both forms of matrices at each of three maintenance intervals, in a 2-back design (1500ms presentation time).

To allow for comparison across the tasks participants' span levels were standardized and a 2 (Task) x 3 (Maintenance Interval) repeated measured ANOVA conducted. This revealed a significant main effect of maintenance interval ($F_{(2,\ 70)} =$

11.675, p < .001 η_p^2 = .250) and no significant interaction, $F_{(4, 70)}$ = .445, p = .363, suggesting that the decay functions of the two tasks did not differ.

7.5.4. Comparison with Experiment 2

Size JND

Comparison between experiment 2 (where the stimuli were employed in a standard protocol) and the present study shows a large difference on the JND task in overall performance ($F_{(1, 32)}$ = 81.436, p < .001 η_p^2 = .718) and no interaction ($F_{(2, 64)}$ = .273, p = .762). This suggests a large impact of the change in procedure on the resolution of the maintained image, but no overall change in decay function.

High Semantic Matrices

The high semantic matrix patterns task showed a significant difference in performance between the two studies, ($F_{(1, 32)}$ = 132.005, p < .001 η_p^2 = .978); mean span level in the standard protocol (9.60) was significantly higher than in the 2-back (5.13). The interaction failed to reach significance ($F_{(2,64)}$ = 1.917, p = .155), however as discussed above, even following Bonferroni corrections in the 2-back procedure participants span level dropped significantly with an increase in maintenance intervals and this effect was not present in the standard protocol.

7.6. Experiment 5: Discussion

The use of a 2-back procedure involves the introduction of a task-relevant visually similar stimulus, in the early work using matrix patterns by Phillips and Colleagues (Phillips and Christie, 1977a; 1977b), this lead to reduced but above chance level performance. Phillips (1983) and several subsequent authors (e.g. Avons and Phillips, 1987) have argued that performance on the pre-recency items is indicative of a representation of the matrix pattern that is maintained in LTVM.

Given that participants were able to complete the high semantic task but not the low semantic task, an important way to consider the results for the two matrix pattern tasks is to consider what differs between the two that would facilitate performance on the high semantic task. Given the only systematic difference between the two forms of matrix pattern is the degree to which they afford semantic representation, it seems plausible that this is the mechanism that is enabling participants to complete the high semantic task. This would suggest that when the patterns are made to rely on their representation in long term visual memory, only representations in the high semantic patterns afford enough semantic description to facilitate above-chance performance. This also suggests that the 2-back procedure may not remove all executive resources from consolidation and maintenance, a notion that will be discussed in chapter 9.

For the size JND, participants were able to maintain performance at above chance level. Given that the data for the matrix patterns suggests that, in this procedure, such performance is indicative of a reliance on LTVM. This suggests that participants were able to form categorical representation of the squares. At the 4.5second maintenance interval, the smallest average size difference participants could detect was a change of 31.33%, this decreased to 38.00% at 11.5seconds. Although a pool of 58 squares is used in the JND task to avoid participants forming LTM representations of the squares, it is plausible that coarse categorical representations such as the labels 'small', 'medium', 'large' in participants' judgements could facilitate performance at the levels seen here.

One possibility, given the levels of performance seen in the JND and the high semantic matrices, is that participants were retaining the representations in the phonological loop. Very coarse representations of size in the JND and very salient semantic features of the matrices may afford verbal labels, this would explain the above chance performance on these tasks in the face of both visual and executive interference. In the initial ratings of the patterns sets (see table 5.1, chapter 5) the high semantic patterns at level 5 (the levels of performance seen in the present study) were given a mean 'meaningfulness' rating of 5.94 out of 7, compared to 4.63 in the low semantic set. This would suggest that the low semantic patterns have fewer obvious chunks or familiar forms and as such a verbal representation may not be enough to facilitate performance. If it is presumed that performance is reliant on a phonological representation in this study, the significant patterns of decay observed in both the high semantic patterns and the JND may represent the need of executive resources or conscious attention to the stimuli to keep the representation in an active state (e.g. Cowan, 2005). The encoding of another subsequent task relevant stimuli and the updating of the stimuli in working memory, may direct resources away from the maintenance and re-activation of the representations. A further possibility is that the representations were also maintained to some degree in a visuospatial format. Walker et al (1993) demonstrated that pre-recency items are affected by visual similarity, the decay function seen in the present experiment could be due to the decaying visuospatial representation. However, if the latter is true and participants are still making use of the visuospatial representation, it would be expected that above-chance performance on the low semantic patterns would be possible.

Clearly, the effects of the executive demands in the present study are complicated by the impact of intervening task-relevant stimuli. Before, the impact of executive demands can be discussed, it is necessary to disentangle the effects of visual interference from executive interference. The following study was conducted to remove the impact of visual interference while still taxing the central executive processes demanded by the n-back procedure.

7.7. Experiment 6: 1-back procedure

As discussed above, the results of Experiment 5 are necessarily complex given the inclusion of a visually similar stimulus between study and test in a 2-back procedure. As such the present study used a 1-back; this was designed to recruit executive resources in the absence of this simultaneous visual interference.

7.8. Experiment 6: Methods

7.8.1. Participants

A total of 48 participants took part (42 females, mean age = 19.55, standard deviation = 4.65; and 6 males; mean age = 22.33, standard deviation = 8.66), these were all undergraduate psychology students at Northumbria University paid in partial course credit. Again, participants were excluded if they had participated in any of the previous experiments.

7.8.2. Design

A mixed design was used in which the visual memory task was a between subjects factor with three levels, Size JND, low semantic Matrices and high semantic Matrices and maintenance interval was a within-subjects factor, again with three levels, 4.5, 8.5 and 11.5 seconds. task administration was computerized and participants’ maximum span level was recorded at each maintenance interval.

7.8.3. Materials and Procedure

Materials and procedure were the same as in Experiment 5, but employing a 1-back rather than a 2-back design to avoid the visual interference. As such participants were responding to say whether the pattern or square on the screen was the same as one seen immediately beforehand (as shown in figure 7.3 below). This also required the inter-stimulus intervals to be changed to 4.5, 8.5 and 11.5seconds as in the previous chapter.

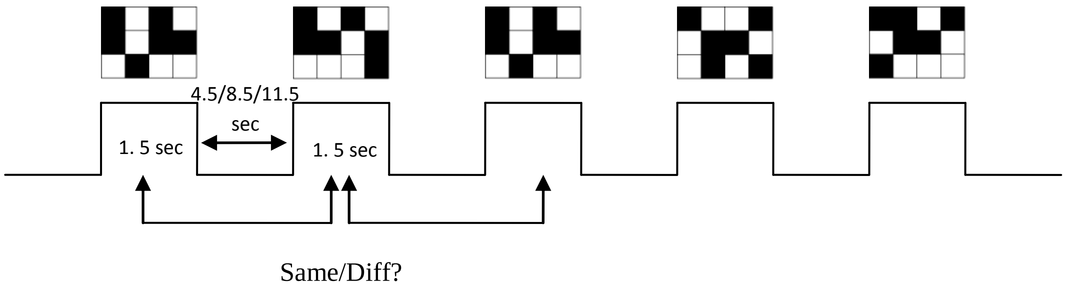


Figure 7.3. 1-back protocol employed for the JND and both forms of matrices.

7.9. Experiment 6: Results

Of the data collected 4 participants data had to be excluded from the low semantic Condition, and 1 from the high semantic condition as they failed to reach the criterion for progression at entry level.

Table 7.2. Mean and Standard Deviations of span level for each 1-back task across three maintenance intervals.

	JND (n = 16)		Low Semantic (n = 14)		High Semantic (n = 15)	
	Mean	SD	Mean	SD	Mean	SD
4.5seconds	15.00	5.16	6.28	1.90	5.93	1.16
8.5seconds	21.25	8.85	5.36	1.08	5.53	0.99
11.5seconds	24.38	8.92	5.29	1.07	5.53	0.99

7.9.1. Analysis of Matrix Patterns

Analysis of the two forms of the matrix patterns task in a 2 (Level of Semantics) x 3 (Maintenance Interval) mixed ANOVA revealed a significant main effect of maintenance interval ($F_{(2, 54)}$ = 8.189; p = .001 η_p^2 = .223) with performance over

4.5seconds being significantly better than 8.5seconds (p = .014) and 11.5seconds (p = .022) but no difference between 8.5 and 11.5seconds (p = 1.000). There was no overall effect of the semantic manipulation (F < 1), and no significant interaction effect ($F_{(2, 54)}$ = 1.415; p = .252).

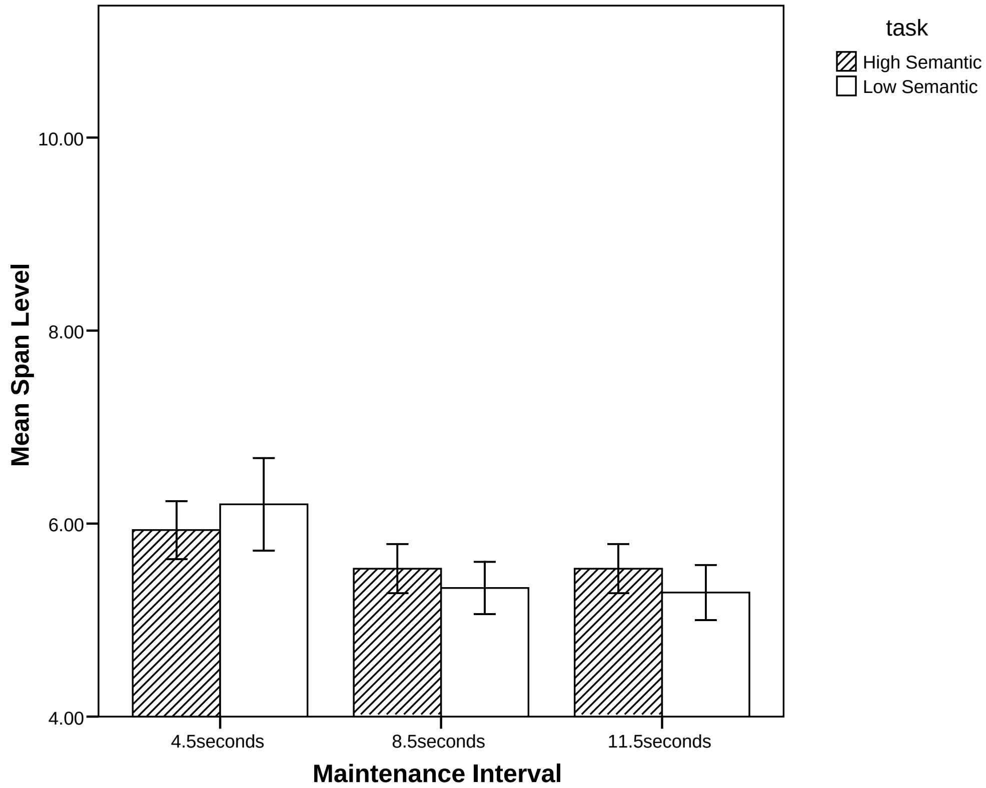


Figure 7.4. Mean span level for the two forms of matrix pattern task across three maintenance intervals, with standard error bars (+/- 1 SE)

7.9.2. Analysis of Maintenance Interval

To investigate the effect of increasing maintenance interval, a one way repeated measures ANOVA was conducted for each task.

Size JND

For the JND task the main effect of maintenance interval was significant ($F_{(2, 30)}$ = 13601, p <.001 η_p^2 = .476). Bonferroni post hoc comparisons showed an identical pattern of performance as in previous studies in the thesis (see table 9.1, Chapter 9, for comparison table). Performance was significantly better at 4.5seconds relative to 8.5s (p=.003) and 11.5s (p=.001) but that the two longer maintenance intervals did not differ from one another significantly (p=.408).

Low Semantic Matrices

Following Bonferroni correction there was a significant effect of maintenance interval for the low semantic matrix pattern task, $F_{(2, 26)} = 5.494$, $p = .010$ $\eta_p^2 = .297$. However, none of the post hoc comparisons reached significance.

High Semantic Matrices

The high semantic matrix pattern task showed no significant main effect of maintenance interval, $F_{(2, 26)} = 2.471$, $p = .103$ $\eta_p^2 = .150$. It is possible that this along with the small effect of maintenance interval on the low semantic task, is due to participants almost performing at floor across the three maintenance intervals.

7.9.3. Analysis of Z Scores

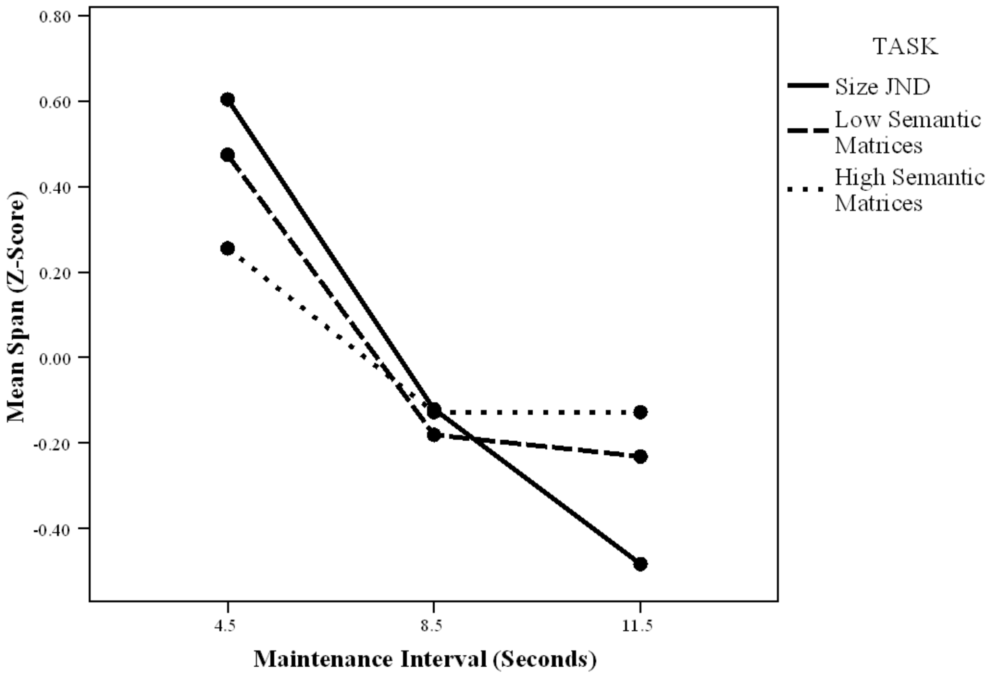


Figure 7.5. Graph Representing mean span (Z-score) for the JND and both forms of matrices at each of three maintenance intervals, in a 1-back design (1500ms presentation time).

To allow for comparison across the tasks participants span levels were standardized and a 3 (Task) x 3 (Maintenance Interval) repeated measured ANOVA conducted. This revealed a significant main effect of maintenance interval ($F_{(2, 84)} = 19.024$, p <

.001 η_p^2 = .312) and no significant interaction, $F_{(4, 84)}$ = 1.439, p = .228, suggesting all three tasks are showing a similar pattern of decay across maintenance intervals.

7.9.4. Comparison with Experiment 2

Size JND

Comparison between experiments 2 (using a standard protocol) and 6 (1-back) shows no significant difference on the JND task in overall performance between the one-back and the standard protocol ($F_{(1, 34)}$ = .187, p = .668) and no interaction between the decay functions of the two ($F_{(2,68)}$ = .825,p = .443), suggesting that performance was unaffected by the change in procedure.

Low Semantic Matrices

For the low semantic matrix patterns task there is a difference across the studies in terms of overall span level achieved ($F_{(1, 30)}$ = 24.141, p < .001 η_p^2 = .446), with average span level using the standard protocol being 8.59 and with the 1-back it was 5.64. However, there was no significant interaction ($F_{(2, 60)}$ = 1.334, p = .271) suggesting the pattern of decay across the three maintenance intervals was unaffected by the change in protocol.

High Semantic Matrices

Finally for the high semantic matrix patterns task there was a significant difference in performance between the two studies, ($F_{(1, 31)}$ = 81.611, p< .001 η_p^2 = .725); mean span level in the standard procedure (9.60) was significantly higher than one back performance (5.66). The interaction was not significant (F < 1).

7.9.5. Comparison between 2-back and 1-back procedures

Comparisons between the two forms of n-back can only be drawn for the high semantic patterns as no participants completed the 2-back low semantic task. A 2 (type of n-back) by 3(maintenance interval) mixed ANOVA was conducted and revealed no significant difference between the two forms of n-back ($F_{(1, 29)}$ = 3.665, p = .065), a significant main effect of maintenance interval ($F_{(2, 58)}$ = 9.786, p<.001 η_p^2 = .252) and no interaction between the two (F < 1). This suggests that there was no additional effect of the 2-back over and above the 1-back for the high semantic patterns.

7.10. Experiment 6: Discussion

The present study aimed to clarify whether the performance on the two forms of matrix pattern task is affected by additional executive demands of the 1-back procedure. Firstly, the JND was shown to be unaffected when used as a 1-back compared to experiment 2 where the matrix patterns were employed in a standard procedure. This suggests that the maintenance of high fidelity representations for size is unaffected by executive interference and that the impact of the 2-back procedure can be attributed to the intervening stimulus causing interference at a visual level (Phillips & Christie, 1977b).

Following 1-back interference both the high and low semantic matrix patterns show equivalent performance. The results from the 2-back task suggest that the low semantic task, when interfered with to the extent of the high semantic task, cannot make sufficient use of the semantic elaboration to allow performance at an above-chance level. However, when the intervening visual stimulus is removed in the 1-back procedure, performance is equivalent to the high semantic patterns, suggesting the low semantic patterns are placing demands on the visual STM component of low semantic pattern representations

7.11. General Discussion

The results for the JND task will be considered first. The large decrement in performance in a 2-back procedure appears to be due to the effect of an intervening visual stimulus (Logie, 1986). When a 1-back procedure is employed, performance is equivalent to that seen under control conditions. Therefore, the level of performance seen in Experiment 5 can be attributed to a pre-categorical representation of size underpinning performance on the task. This provides additional support for the increasing body of research suggesting that the Size JND task is one which is relatively free of executive demands (e.g. Hamilton et al 2003; Thompson et al, 2006).

It was noted in Experiment 1 that there was a significant effect of verbal executive tasks on the Size JND. Although this effect was small it is important to consider the nature of this interference. It was discussed in Chapter 4 that the secondary executive tasks employed in experiment 1 placed heavy demands on general executive resources, in the tasks participants were constantly required to divide attention between the JND and the executive tasks. Barrouillet et al (2004) propose a Time-Based Resource-Sharing model in which dividing attention between tasks will result in a decay in performance, the longer attention is switched away in aid of the processing of one task, the greater the decay in the other task. In the 1-back task, participants must only divide attention between the encoding and storage of the stimulus and its comparison with the previous stimulus during presentation. It was demonstrated in Experiment 4 that there was no increase in performance on the JND between 500msec and 1500msec presentation times, suggesting that the stimulus in the 1-back may have been presented for sufficient time to allow comparison with the study stimulus in memory and encoding of the test stimulus. It seems plausible therefore that the interference observed in Experiment 1 reflects demands the Size JND places on attentional resources. This will be investigated further in the following chapter.

The 2-back study was employed in part to replicate the effects seen by Phillips and Christie (1977a; 1997b), whereby presenting subsequent task-relevant stimuli leads to visual matrices being represented in LTVM or offline. This procedure lead to all participants being unable to perform the low semantic pattern task even at entry level pattern size (8 cells with 4 filled in black). This is perhaps indicative of the categorical representations of such patterns being insufficient to facilitate change detection performance at an above-chance level. When performed as a 1-back task, the effects of visual interference were removed, leaving only the impact of executive resources. In contrast to the 2-back procedure, participants were able to perform the task as a 1-back. However, performance was still largely impaired (mean span = 5.64) relative to when performed in the standard procedure (mean span = 8.59).

For the high semantic task, in contrast to the low semantic task, participants were able to perform the task under 2-back interference. This may be indicative of salient or coarse semantic representation being held in a verbal format, although it is also possible that categorical representations were formed and stored passively. In the Cowan (2005) model, it is made explicit that some salient semantic features may be activated automatically and can remain active outside of the focus of attention in short-term memory. This would allow for a passive or automatic categorical representation that doesn't demand executive resources. This cannot be accommodated readily in the Baddeley (2000) model, as the activation of categorical representation is presumed to be a function of the episodic buffer which is in turn proposed to rely on executive functioning for encoding and consolidation into the episodic buffer. This issue will be discussed at length in chapter 9.

However, the results suggest that the high semantic patterns were able to be represented in a categorical form (perhaps rehearsed in the PL) to allow sufficient quality of the representation for accurate change detection performance. This representation is likely to be equivalent to the pre-recency items in the work of Phillips and Christie (1977a; 1977b). When the visual interference of the intervening stimulus is removed in the 1-back procedure, leaving only the executive interference, performance on the high semantic task (mean = 5.66) is equivalent to the low semantic task (mean span = 5.64). If the binding or maintenance of the bound categorical representations of the pattern and the visual representation of the same pattern is dependent on executive resources, then the level of performance under 1-back interference may be indicative of the maximum sized pattern that can be represented in the absence of such executive resources.

This lends support for research that proposes central executive resources are only required for chunking when the capacity of temporary memory is exceeded (e.g. Jeffries et al, 2004; Rudner & Ronnberg, 2008). As executive resources are denied in this study, the levels of performance seen under 1-back interference may represent the maximum capacity of visual STM. As this is a passive process it would be attributed to the VSSP in Baddeley's (2000) model, however, the activation of some categorical information goes against this. In Cowan's (2005) model, he specifies that a capacity limit to activated memory is necessary to distinguish it from long-term memory; it is possible that this pattern size reflects a capacity limit for information activated but held outside of the focus of attention.

Ichikawa (1985, and more recently Kemps, 1999) proposed two forms of complexity in visual patterns, firstly *quantitative complexity* which is complexity defined by physical characteristics such as pattern size and certain gestalt characteristics. Secondly, *structural complexity* which is defined by higher level features such as varying types of redundancy and perhaps semantics. Chipman and Mendelson (1979) demonstrated that in children's ratings of complexity in matrix patterns, only quantitative factors contributed to the overall rating. It is possible that this represents the under-developed strategic processing in children (Pickering, 2001). It would therefore follow that in the absence of executive resources observed in experiment 6, performance observed is related to the quantitative factors associated with the visual patterns. This would explain why there is no difference in performance levels on the high and low semantic tasks; the two only differ strategically in terms of their structural complexity. The span level observed in both formats, is perhaps indicative of maximum span level for visual matrices, represented in a visual format constrained solely by quantitative factors.

Several putative confounds are present in this series of studies that prevent sufficient conclusions being drawn here. One possibility is that comparing the study pattern with the test pattern reduced the amount of time available for encoding. If this were the source of the decrement in performance, span levels achieved would be akin to those where encoding time is limited. However, this seems unlikely as performance in the present chapter was significantly worse than that seen in Experiment 4, where encoding time was manipulated. Furthermore, as mentioned above, the executive interference employed in this chapter persists throughout all stages of the task. To delineate the impact of executive resources on the encoding and maintenance of the bound representations, it is necessary to constrain the executive interference to the maintenance interval only.

Although, executive interference can prevent the maintenance and rehearsal of fine visual detail, it is possible that when presented during encoding it may result in a poorer initial activation of categorical information. Cowan (1988) proposes that all stimuli activate some elements in long term memory but that this activation is enhanced for attended stimuli. If a participant is unable to attend to a stimulus some features will still be activated in memory and compared to the neural model but most semantic features won't be processed automatically. This supports the notion that interfering with executive resources (which control attention) or occupying attention will result in participants not making use of the possibility of additional semantic representation that the high semantic patterns afford.

As such, the initial experiment in the following chapter will investigate the impact of dividing attention on the three tasks. It has also been discussed in this chapter that very coarse representations of size in the JND and very salient semantic labels in the high semantic matrices may be maintained with the help of phonological processes and that performance observed on the low semantic matrices and the Size JND in experiment 5 was affected by the introduction of an intervening visual stimulus. One aim of the following chapter is to assess the relative impact of visual and phonological interference on the three tasks. Chapter 8 will also serve to address concerns regarding the impact on encoding time in the present chapter by employing interference only in the maintenance interval.

7.12. Chapter Summary

The present chapter further investigated visual matrix patterns which vary in the degree to which they afford semantic representation, participants' abilities to maintain the representations offline and in the face of executive interference. The results suggest that when forced offline in a 2-back procedure and perhaps stored in categorical form, participants were unable to maintain sufficient representations of the low semantic patterns to allow above chance performance at every level of the task. In contrast, participants were able to perform the high semantic task. In a 1-back procedure, where participants could represent the patterns online but with limited access to executive resources, performance on the high semantic task was equivalent to the low semantic task. It is proposed that this level of performance represents the maximum span level for a visual pattern represented in a visual short term memory that is constrained by quantitative complexity of the pattern.

The size JND was greatly affected when forced offline by an intervening stimulus in experiment 5, but participants were able to represent the squares at a very coarse level, possibly in a categorical form. In the 1-back procedure, performance of the Size JND didn't differ from performance in the standard procedure, providing support for the use of the Size JND as a visual task which places relatively few demands on executive resources. The following chapter will attempt to further specify the effects of executive, visual and phonological interference by employing secondary tasks in the maintenance period only.

CHAPTER 8

Identifying the Functional Architecture Underlying Visual Memory Maintenance

8.1. Chapter Overview

The previous chapter demonstrated a separation between the high and low semantic tasks in terms of the extent to which they afford semantic representation. When presented with a task relevant intervening stimulus in a 2-back procedure, participants were unable to perform the low semantic task, suggesting it cannot be sufficiently represented in a categorical form. Executive interference caused by a 1-back procedure lead to equivalent performance on both forms of matrix pattern task. This level of performance was tentatively suggested to represent maximum span of visual short term memory defined by quantitative complexity of the matrices. However, the impact of executive interference could not be localised to one process. As such the present study employs interference during maintenance only, in a dual task procedure. The aim of this final empirical chapter is to identify the working memory functional architecture underlying the maintenance of the Size JND, high and low semantic tasks.

8.2. Background

The previous chapter established that transforming both forms of matrix pattern task into 1-back procedures, thereby increasing the demands placed on executive resources, lead to a large impairment to performance and performance on both tasks being equivalent (mean span for low semantics = 5.64; high semantic = 5.66). A tentative conclusion was drawn in section 7.11, suggesting that these levels of performance were indicative of the maximum span for matrices held in a visual format, constrained only by quantitative complexity as defined by visual processes.

However, a limitation to the studies in the previous chapter was that executive interference during encoding and maintenance were not differentiated. A further concern was that the nature of the protocol used reduced the amount of attention participants could allocate to encoding. A reduction in encoding time was shown in Experiment 4 to be detrimental to performance of both forms of matrix pattern task but more so to the high semantic task. As such the initial study in the present chapter is concerned with executive interference on the tasks during maintenance only, using the standard procedure employed in chapter 6.

If the impact of executive interference is occurring during the maintenance interval, this would suggest that the central executive (or attentional resources) is involved in the maintenance of the matrix patterns. The impact of the 1-back procedure in experiment 6 was not significant for the Size JND, supporting the notion of it being relatively free of executive demands. However, Experiment 1 demonstrated an impact of general executive interference on the JND, perhaps indicating a role of attention in the maintenance of the stimulus.

The nature of the binding of multiple representations into a single episode has been discussed throughout the thesis and research has been presented regarding memory for prose. Memory for prose is known to involve the integration of phonological and long-term representations (Baddeley, 2007). As discussed in chapter 3, such research has produced inconclusive results regarding the executive demands placed by binding (e.g. Allen & Baddeley, 2008; Chalfronte & Johnson, 1996; Jeffries et al, 2004; Naveh-Benjamin et al, 2004). The previous chapter showed an impact of executive interference in performance of matrices relative to the JND. To localise the executive interference observed, the first study in this chapter aims to assess the contribution of executive resources (more specifically, attention) in the maintenance interval alone.

The subsequent studies will then aim to identify the contributions made by verbal and visual short term memory to task performance. The integration of LTM semantic information is required for the chunking of matrix patterns into fewer informational units. However, maintaining the ‘labels’ of familiar forms identified within a matrix may involve rehearsal in verbal short term memory, as discussed in the previous chapter. It is possible that the advantage seen for high semantic patterns over low semantic patterns in the two back procedure of experiment 5 is verbal in nature. It is possible that very obvious parts of the patterns (i.e. letters or familiar shapes) may be represented and rehearsed verbally, without the need for executive resources to chunk the pattern. As the high semantic patterns contain more ‘familiar forms’ it is possible that these patterns also afford more verbal representation. Experiment 8 will examine this. The final experiment will serve to confirm the involvement of visual short term memory across the range of tasks.

8.3. Experiment 7: Attentional Interference

It was shown in Experiment 1 that the executive resources recruited in performance of the Corsi blocks task, memory for visual matrices and the Size JND are general in nature. The impact of secondary executive interference was demonstrated to be dependent only on the overall processing demands made by the secondary task. Barrouillet et al (2004) proposed a Time-Based Resource-Sharing hypothesis (TBRS) of processing and storage in which both require attention and that memory traces of to-be-remembered information decay as soon as attention is switched away in aid of processing.

The TBRS model would suggest that capturing attention by the need to process a secondary task, would impact the storage of information needed for performance in the primary task. As such, if a secondary task is employed which isn't necessarily complex in its demands but constantly captures attention, it will prevent participants from refreshing the stored representations.

Lepine et al (2005) devised a *continuous operation span task* in which the concurrent task is a computer paced simple processing task (adding and subtracting 1 to a single digit), proposing that a simple task that requires continuous processing and as such prevents switching would be highly detrimental to span. They varied the pace of the operands and confirmed that the effect of concurrent activity on span is dependent on the extent to which it captures attention with a fast enough rate leading to performance equivalent to that of traditional operation span (discussed in chapter 2). In a further experiment they eliminated the possibility of this being due to the effects of articulatory suppression by requiring a key-press response and replicating the same effects.

In the present study, the continuous operation span task will be employed to tax executive resources in the maintenance period. It is predicted that performance on the two matrix tasks will be similar to the effects observed in study 6. The fact that attention is constantly captured may result in performance being worse than in study 6 as the 1-back procedure may not have captured attention sufficiently to prevent participants switching attention back to the representation to be stored in between processing episodes.

8.4. Experiment 7: Methods

8.4.1. Participants

A total of 39 participants took part (24 females, mean age = 20.75, standard deviation = 2.89 and 14 males; mean age = 24.27, standard deviation = 4.20), these were all undergraduate psychology students at Northumbria University paid in partial course credit. Participants were excluded if they had taken part in any previous studies in the thesis.

8.4.2. Design

A mixed design was used in which the visual memory task was a between subjects factor with three levels, Size JND, low semantic Matrices and high semantic Matrices. Maintenance interval was the within-subjects factor with three levels, 4.5, 8.5 and 11.5 second maintenance intervals. Task administration was computerized and participants' maximum span level was recorded at each maintenance interval.

8.4.3. Materials

Size Just Noticeable Difference (Size JND)

Procedure for the JND was the same as in Experiment 2 with a variable maintenance interval (4.5, 8.5 or 11.5seconds). Participants completed a maximum of 20 trials at each level of difficulty (the difference between study and test stimuli decreasing across 5 difficulty levels: 40%, 30%, 20%, 10% and 5%), with criterion for progression being set at 15/20 (or a binomial probability of <.05) and maximum span level being taken as the last level successfully completed. Participants completed the task at all maintenance intervals and span level achieved was recorded.

High- and Low- Semantic Matrix Patterns Task

Participants completed a recognition version of both forms of the matrix pattern task described in chapter 5. Entry level was 10 cells (measuring 10mm x10mm) with 5 filled this increased to a maximum of 30 with 15 filled. Participants completed a computerized version of this to ascertain their span level at each of the three maintenance intervals completing up to 20 trials at each level of difficulty, as in the JND criterion for progression being 15/20 (binomial $p < .05$) to counter the 0.5 probability for guessing.

For all tasks the stimuli were presented in an array measuring 160mm x 160mm and participants were seated to ensure a viewing distance of approximately 55cm.

Attentional Interference Task

The secondary task employed was one used by Lepine et al (2006) in which participants are presented with a root number on screen (offset from test/study stimuli) for 500msec which they are required to say out loud (a single digit between 1 and 9), they are then provided with a simple operation to carry out on that number (ether plus or minus one, presented on screen for 250msec) which they must carry out and say the answer out loud. Following 750msec a second operation is presented (again, either plus or minus one) which they must carry out on the solution to the previous operation. This continues for the duration of the maintenance interval.

8.4.4. Procedure

In all tasks stimuli were presented for 1500msec followed by the variable maintenance interval and then the probe stimulus presented until response or timeout after 4000msec. Testing was blocked by maintenance interval and took place in one session lasting approximately 1 hour, order of administration of the task at three different maintenance intervals was randomized for all participants and trials were randomized within each level.

8.5. Experiment 7: Results

Table 8.1. Mean and Standard Deviation span level for each task under attentional interference across three maintenance intervals

	JND (n = 12)		Low Semantic (n= 15)		High Semantic (n=12)	
	Mean	SD	Mean	SD	Mean	SD
4.5seconds	28.33	7.17	5.53	0.52	5.83	1.03
8.5seconds	30.00	7.39	5.13	0.35	5.58	1.16
11.5seconds	31.67	8.35	5.27	0.80	5.50	1.17

8.5.1. Analysis of Matrix Patterns

Analysis of the two forms of the matrix patterns task in a 2 (level of semantics) x 3 (maintenance interval) mixed ANOVA revealed a significant main effect of maintenance interval ($F_{(2, 50)} = 4.656$, $p = .014$ $\eta_p^2 = .157$), but that this is limited to the difference between 4.5 and 8.5seconds ($p = .039$). There was also no effect of the semantic manipulation ($F_{(1, 25)} = 1.152$, $p = .293$) and no significant interaction ($F < 1$).

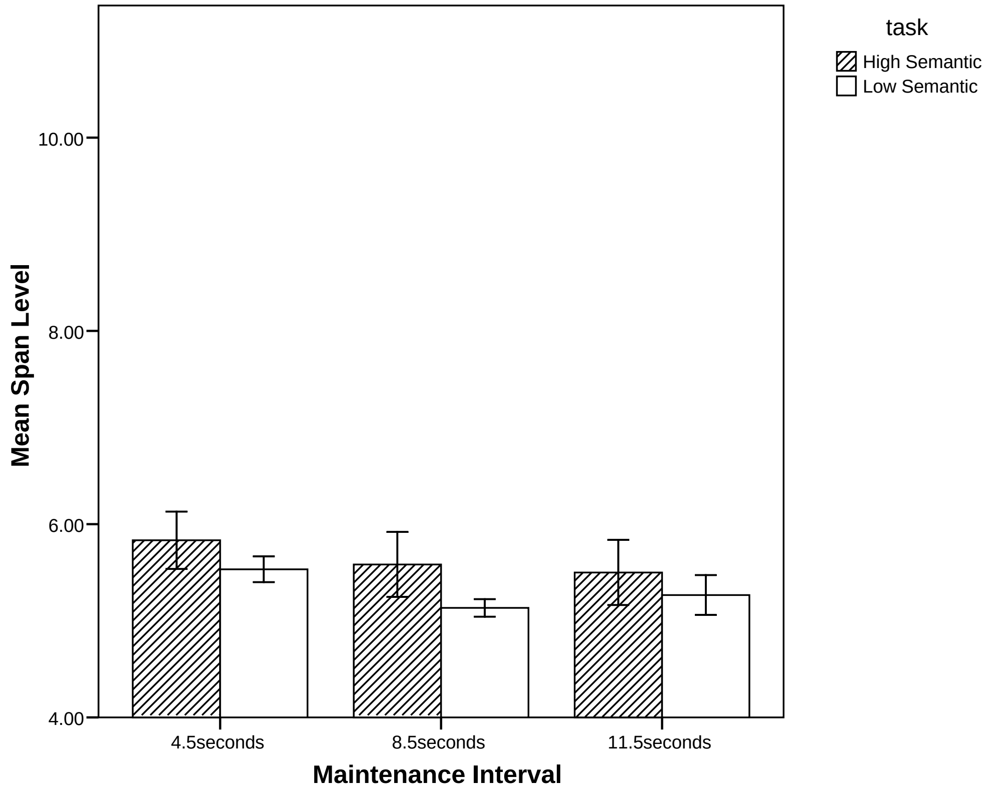


Figure 8.1. Graph of mean span levels of two forms of matrix pattern task under attentional interference across three maintenance intervals, with standard error bars (+/- 1 SE)

8.5.2. Analysis of Maintenance Interval

To investigate the effect of maintenance interval on the individual tasks, one way repeated measures ANOVAs were conducted for each task. Following Bonferroni correction there was no significant effect of maintenance interval for the low semantic matrix pattern task ($F_{(2, 28)} = 3.213$, $p = .165$), the high semantic matrix pattern task ($F_{(2.22)} = 2.014$, $p = .471$) or the JND ($F < 1$).

8.5.3. Analysis of Z scores

Comparisons were made across the three tasks using Z-Scores and showed a significant main effect of maintenance interval ($F_{(2, 72)} = 3.950$, $p = .024$ $\eta_p^2 = .099$), although following Bonferroni corrections there were no significant differences between maintenance intervals (all $p > .05$). There was also no significant interaction ($F < 1$).

8.5.4. Comparison with Experiment 2

Size JND

Comparison between experiment 2 and the present study shows a significant difference on the JND task in terms of overall performance ($F_{(1,30)} = 26.371$, $p<.001$ $\eta_p^2 =.468$) with performance under control conditions (mean span = 21.00) being significantly better than under attentional interference (mean span = 30.00). Despite the effect of maintenance interval reaching significance under control conditions and not in the present study, there was no interaction between the two decay functions ($F < 1$).

Low Semantic Matrices

For the low semantic matrix patterns task there was a significant difference across the studies in overall span level achieved ($F_{(1,31)} = 39.389$, $p <.001$ $\eta_p^2 =.560$) with span level under control conditions (mean span = 8.59) being significantly greater than under attentional interference (mean span = 5.31). There was also a significant interaction between the two formats ($F_{(2, 62)} = 6.624$), $p = .002$ $\eta_p^2 = .176$) due to the decay function being significant for the control task and not under attentional interference.

High Semantic Matrices

Finally for the high semantic matrix patterns task there was a significant difference in performance between the two studies ($F_{(1, 28)} = 65.649$, $p < .001$ $\eta_p^2 =.701$) with mean span under control conditions (9.60) being significantly greater than under attentional interference (5.63). However, there was no significant interaction ($F< 1$).

8.6. Experiment 7: Discussion

In experiment 6 of the previous chapter the potential impact of executive interference on maintenance in all three tasks was compromised due to the possible impact on encoding and retrieval. The present study aimed to separate out these effects by presenting executive interference in the maintenance interval only. The executive task chosen was one which was designed to constantly demand attentional resources (Lepine et al, 2006).

The results of the present study have shown that the introduction of such interference impairs performance on both forms of the matrix patterns task, leading to almost equivalent levels of performance (mean span on the low semantic task = 5.31; high semantic = 5.63). This level of performance is very similar to that seen under 1-back interference in experiment 6.

The JND was also significantly affected by the introduction of the attentionally demanding executive task; this effect was not observed in experiment 6. There are several possible causes of this interference. Firstly, in the attentionally demanding task, the operations were presented visually. As such the interference observed could have been caused by visual interference, however, this is somewhat unlikely. The operands were always offset from the stimulus to avoid masking (shown to cause interference; Neisser & Becklen, 1975); the operands weren't semantically similar to the JND stimuli (Hirst & Kalmar, 1987) and did not compete for storage in visual memory. A second possibility is concerned with the fact that the secondary task was intentionally designed to constantly capture attention. It is possible that the maintenance of high fidelity size information is demanding of visual attention, if so the present study would have prevented this. The 1-back procedure, despite demanding executive resources, may not have prevented participants switching attention to the storage of the stimulus. Having prevented participants allocating visual attention to the maintenance of the stimulus, performance levels observed (30% change detection) are similar to performance under 2-back interference (35% change) where participants were reliant on a categorical representation for size. In the Cowan model, when attention is occupied, the visual detail of the JND stimulus would be represented outside of the focus of attention. This is in short term memory, where visual representations decay rapidly

(Cowan, 1988) without being refreshed by entering the focus of attention the high fidelity information would be lost.

Before conclusions can be drawn regarding the impact of the attentional interference on the tasks, the additional demands of the attentional task must be controlled for. Firstly, as discussed above, it is possible that the task could have placed demands on visual processes; as such experiment 9 includes a visual interference paradigm. As response was oral, there is the possibility of an impact of verbal interference, although this is unlikely as Lepine et al (2006) showed no difference between oral and key-pressing responses in the same task.

8.7. Experiment 8: Phonological Interference

One possible cause of the effects observed in study 7 is that the oral response disrupted storage of task-relevant information in verbal short term memory. Lepine et al (2006) controlled for this by also employing the continuous operation span task with a key-press response and found equivalent effects. However, given the nature of the matrices employed in the present study, controlling for phonological involvement is necessary.

Brown et al (2006) conducted categorization of visual matrices similar to that seen here, separating the VPT stimuli (Della Sala et al, 1997) into high and low verbalizable patterns. Finding improved performance for high verbalizable patterns above the low verbalizable patterns. Although the present study didn’t classify the patterns in terms of verbal representation alone, it is plausible that some of the *semantic* forms present in the matrices would be rehearsed with *verbal* labels during maintenance.

Irrelevant speech (IS) has been known as a disruptor of phonological information for some time (e.g. Salamé & Baddeley, 1982; Beaman & Jones, 1997). A series of changing utterances during or immediately following the presentation of a to-be-recalled list of words impairs performance by up to 50% (Ellermeier & Zimmer, 1997). The present study employs IS as the secondary task as it is possible that in the high semantic task, participants are able to represent the patterns using a verbal code (as discussed in chapter 7). This would explain the above chance performance on the 2- back task, where access to executive and visual resources was denied.

8.8. Experiment 8: Methods

8.8.1. Participants

A total of 45 participants took part (31 females, mean age = 23.48, standard deviation = 6.46 and 14 males; mean age = 20.86, standard deviation = 2.36), these were all undergraduate psychology students at Northumbria University, who had not taken part in any of the previous studies, and were paid in partial course credit.

8.8.2. Design, Materials and Procedure

The procedure was identical to that in the previous study but with IS in the maintenance interval

Irrelevant speech

Previous studies (e.g. McConnell & Quinn, 2004) have noted that when using normal speech, gaps in speech can vary and therefore alter the effective duration of speech when presented in the maintenance interval alone. As such, the primary tasks were identical to the previous two studies but with irrelevant speech presented along with the first trial and remaining active throughout the study. The IS used was Norwegian, spoken at normal speed by a male native speaker and was delivered through headphones.

8.9. Experiment 8: Results

Table 8.2. Mean and Standard Deviation span level for each primary task under interference by irrelevant speech, presented for each of the maintenance intervals

	JND (n = 16)		Low Semantic (n = 15)		High Semantic (n = 14)	
	Mean	SD	Mean	SD	Mean	SD
4.5seconds	15.31	5.62	8.20	2.08	10.07	2.64
8.5seconds	20.31	7.41	7.67	2.29	8.92	2.53
11.5seconds	25.94	9.53	7.13	1.68	9.07	2.37

8.9.1. Analysis of Matrix Patterns

Analysis of the two forms of matrix patterns task in a 2 (level of semantics) x 3 (maintenance interval) mixed ANOVA revealed a significant main effect of maintenance interval $F_{(2, 54)} = 7.78$, $p = .001$ $\eta_p^2 = .224$). Bonferroni post hoc comparisons show performance was greater at 4.5 than at 8.5 ($p = .036$) and 11.5seconds ($p<.001$) but that there was no difference between the latter two ($p=1.00$). There was also a significant main effect of semantic manipulation ($F_{(1, 27)} = 4.661$, $p = .040$ $\eta_p^2 =.147$), with the high semantic task demonstrating significantly higher performance than the low semantic. There was also no significant interaction between semantics and maintenance interval ($F < 1$).

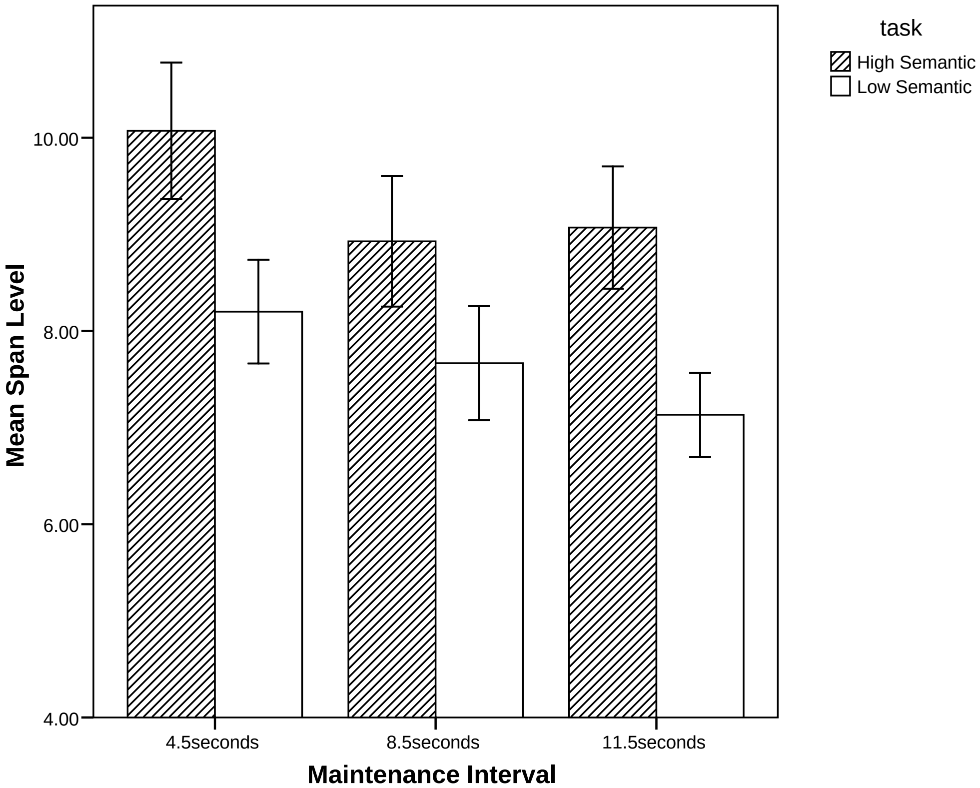


Figure 8.2. Mean Span level for two forms of matrix pattern task under interference by irrelevant speech, presented across three maintenance intervals with standard error bars (+/- 1 SE)

8.9.2. Analysis of Maintenance Interval

To investigate the effects of increasing maintenance interval, one way repeated measures ANOVAs were conducted for each task.

Size JND

Finally, for the JND the main effect of maintenance interval was significant ($F_{(2, 30)}$ = 10.446, p < .001 η_p^2 = .411), post hoc comparisons showed performance at 4.5seconds was significantly better than at 8.5 (p = .046) and 11.5 (p = .005) but the latter two did not differ (p = .070).

Low Semantic Matrices

In contrast to previous experiments, following Bonferroni correction there was no significant main effect of maintenance interval for the low semantic matrix pattern task ($F_{(2, 28)}$ = 2.791, p = .234).

High Semantic Matrices

The high semantic matrix pattern task showed a significant main effect of maintenance interval ($F_{(2, 26)}$ = 7.925, p = .006 η_p^2 = .379), post hoc comparisons showed performance at 4.5seconds was significantly better than at 8.5 (p=.012) and 11.5 (p=.015) but the latter two did not differ (p = 1.000). Suggesting the verbal representation of the stimulus was contributing towards the stability of the representation seen under control conditions.

8.9.3. Analysis of Z-Scores

To allow for comparison across the tasks, participants span levels were standardised and a 3 (task) x 3 (maintenance interval) repeated measures ANOVA was carried out. This revealed a significant main effect of maintenance interval ($F_{(2, 86)}$ = 16.115, p <.001 η_p^2 = .277) and no interaction ($F_{(4, 84)}$ = 4.248, p = .054).

8.9.4. Comparison with Experiment 2

Comparison between experiments 2 and the present data shows no significant changes in overall performance on the JND ($F_{(1, 34)}$ = .085, p = .772), the low semantic matrix patterns task ($F_{(1,31)}$ = 1.979, p = .169) or the high semantic matrix patterns task ($F_{(1,30)}$ = .117, p = .735). None of the interactions reached significance (all p’s > 0.10)

8.10. Experiment 8: Discussion

Firstly, the results for the Size JND showed no significant effect of IS. This is consistent with the work of McConnell and Quinn (2004) who employed a similar Size JND task using circles and demonstrated its robustness to irrelevant speech. This, taken with the results of the 2-back task in experiment 5, suggests that the Size JND is represented in a visual (non-verbal) modality. Although the interaction between JND combined with IS and the JND control performance (experiment 2) did not reach significance, at the longest maintenance interval there was a trend towards the interference effects becoming significant. This could be representative of an increasing reliance on a coarse representation of size as the mnemonic representation of the visual stimulus decreases in fidelity. However, this effect was not significant in the present study. It would be interesting to further study the differential effect of visual and verbal interference on the JND at fine and coarse levels of representation.

The low semantic matrix patterns failed to show a significant effect of IS. Furthermore, in contrast to control performance on the task, the decay function of the task was also not significant. In the present study performance on the low semantic matrices at 4.5s showed a mean span of 8.20, decreasing to 7.13 at 11.5seconds, this drop in performance is equivalent to that seen in the previous studies. However, variance was greatly increased in the present study. There are two possible explanations for this. Firstly, this may reflect the power of the study and it is possible that collection of more data would result in the decay function becoming significant. A second possibility is that the larger variance seen here is indicative of individual differences in strategies used, it is possible that only some participants attempt to verbally code the stimuli, as such IS would only affect those participants doing so. Engle et al (1999) propose that individual differences in span performance are especially important when the task involves maintaining task information in the face of distraction or interference. Further research is perhaps needed to examine individual strategies employed in performance of these tasks in the face of various distracters.

The high semantic matrix patterns showed significant decay across increasing maintenance intervals; this effect was not present when the task was performed in the absence of interference. It is possible that the increase in decay is indicative of there being a detrimental effect of irrelevant speech on the high semantic matrix patterns. This would be consistent with the work of Brown et al (2006) suggesting that visual matrices can be supported by verbal recoding of a stimulus. This would also lend support for the notion that the above chance-level performance that was observed in the 2-back procedure, may be due to the high semantic patterns being represented in a verbal form without the need for executive resources. This has interesting theoretical implications that will be discussed in chapter 9.

It is clear however that the effects observed here are not of the magnitude of the effects observed for the attentional interference in experiment 7. This supports the notion of the effects in the previous study being due to the continuous operation task capturing attention throughout the maintenance interval not solely the demands it places on phonological processes, supporting the suggestions by Lepine et al (2006).

8.11. Experiment 9: Visual Interference

An assumption that has been made throughout the present thesis is that all three tasks place demands on visual resources. This final study will investigate this assumption by including a visual secondary task, known to interfere with the maintenance of visual information.

Dynamic Visual Noise (DVN), a display of randomly and rapidly changing black and white dots, was developed as a secondary task by Quinn and McConnell (1996). It is proposed as a technique that can interfere with the encoding, maintenance and retrieval of purely visual information in working memory. The detrimental effects of DVN have been observed on a range of visual imagery tasks such as the mnemonic methods of Pegwords and Loci (McConnell and Quinn, 2000; 2004; Quinn and McConnell, 1996a, 1996b, 1999). Furthermore, Smyth and Waller (1998) observed detrimental effects of DVN on imagery of a climbing route and Dean, Dewhurst, Morris and Whittaker (2005) demonstrated a detrimental effect of DVN on an imagery-based distance judgement task using comparison of size. However, studies have also showed that memory for visual matrices may be unaffected by the introduction of DVN in the maintenance interval (e.g. Andrade et al, 2002; Zimmer & Speiser, 2002; Avons & Sestieri, 2005).

Although research has clearly demonstrated the involvement of visual short term memory in visual matrix task performance (e.g. Avons & Mason, 1999; Thomson et al, 2006; Walker et al, 1993), the present thesis has also demonstrated that memory for visual patterns involves processes above and beyond visual short term memory, a notion supported by previous literature (e.g. Phillips & Christie, 1977b; Avons & Phillips, 1987; Thompson et al; 2006).

McConnell and Quinn (2004) employed a task similar to the Size JND and demonstrated that relatively small changes in size are susceptible to DVN, they propose that DVN produces degradation of visual properties of a stimulus but not to the extent that it could impair performance on matrices when supported by LTM. It may be that the lack of an effect of DVN on matrices is related to the extent to which LTM scaffolding is involved in the representation of the stimulus set employed. The present thesis has demonstrated striking difference between high and low semantic matrices in terms of the effects of limiting encoding duration, including intervening visual stimuli and their decay functions. As such the small, but significant, effects of DVN observed in the literature may be sufficient to impair performance on matrices when the involvement of LTM is limited in the low semantic task.

Dean, Dewhurst and Whittaker (2008) point out the inconsistencies in the type of DVN employed in the literature with rates of change ranging from 5% (Andrade et al, 2002) through to 50% (Dean et al, 2005). It has been demonstrated that a rate of change of 50% impairs performance relative to 20% (Dean et al, 2005), as such the present experiment will employ a 50% rate of change. With this rate of change Dean et al (2008) demonstrated a detrimental effect of the DVN on memory for textures, but not matrices. Although, they attempted to control for LTM involvement to some degree by removing patterns that were symmetrical or contained shapes resembling letters and numbers, the present thesis has demonstrated that LTM can be involved in more abstract forms of visual semantics as well. It is predicted in the present study that DVN at this rate of change will interfere with the low semantic but not the high semantic matrices. Further to this, McConnell and Quinn (2004) demonstrated a detrimental effect of DVN on a Size JND task employing circles, it is therefore predicted that this will be replicated in the present study.

8.12. Experiment 9: Methods

8.12.1. Participants

A total of 48 participants took part (37 females; mean age 20.68, standard deviation = 3.84 and 11 males; mean age = 23.00, standard deviation = 2.57), these were all undergraduate psychology students at Northumbria University paid in partial course credit. None of the participants had taken part in the previous studies.

8.12.2. Design, Materials and Procedure

Dynamic Visual Noise

The present experiment was identical to that employed in Experiments 7 and 8; however, participants were presented with Dynamic Visual Noise in the maintenance interval. The DVN employed was that used by Dean et al (2008) which consisted of a grid of 80 x 80 cells each measuring 2 x 2 pixels. At all times half of the cells were black and half white and the colour of the cells changed at a rate of 50% per second. The DVN was located in the centre of the screen in such a manner that the study and test stimuli always fell within the boundaries of the DVN which began at the offset of the study stimulus and stopped immediately before the test stimulus.

8.13. Experiment 9: Results

Table 8.3. Mean and Standard Deviation span level for each task under interference by DVN, presented across three maintenance intervals.

	JND (n = 16)		Low Semantic (n=16)		High Semantic (n=16)	
	Mean	SD	Mean	SD	Mean	SD
4.5seconds	21.88	6.55	8.00	2.07	9.81	2.99
8.5seconds	26.88	6.02	7.38	2.36	8.75	2.62
11.5seconds	29.38	7.72	6.69	1.78	9.13	2.90

8.13.1. Analysis of Matrix Patterns

Analysis of the two forms of the matrix patterns task in a 2 (level of semantics) x 3 (maintenance interval) mixed ANOVA revealed a significant main effect of maintenance interval ($F_{(2,\ 60)}$ = 9.649, p<.001 η_p^2 = .243). Bonferroni post hoc comparisons showed performance was greater at 4.5s than 8.5 (p = .009) and 11.5 (p < .001) but that there was no significant differences between the two longer maintenance intervals (p= 1.000). There was also a significant effect of the semantic manipulation ($F_{(1,\ 30)}$ = 5.054, p = .037, η_p^2 =.144) with performance on the high semantic task (mean span = 9.23) being significantly higher than on the low semantic task (mean span = 7.36). However, there was no significant interaction effect ($F_{(2,\ 60)}$ = 2.377, p = .107).

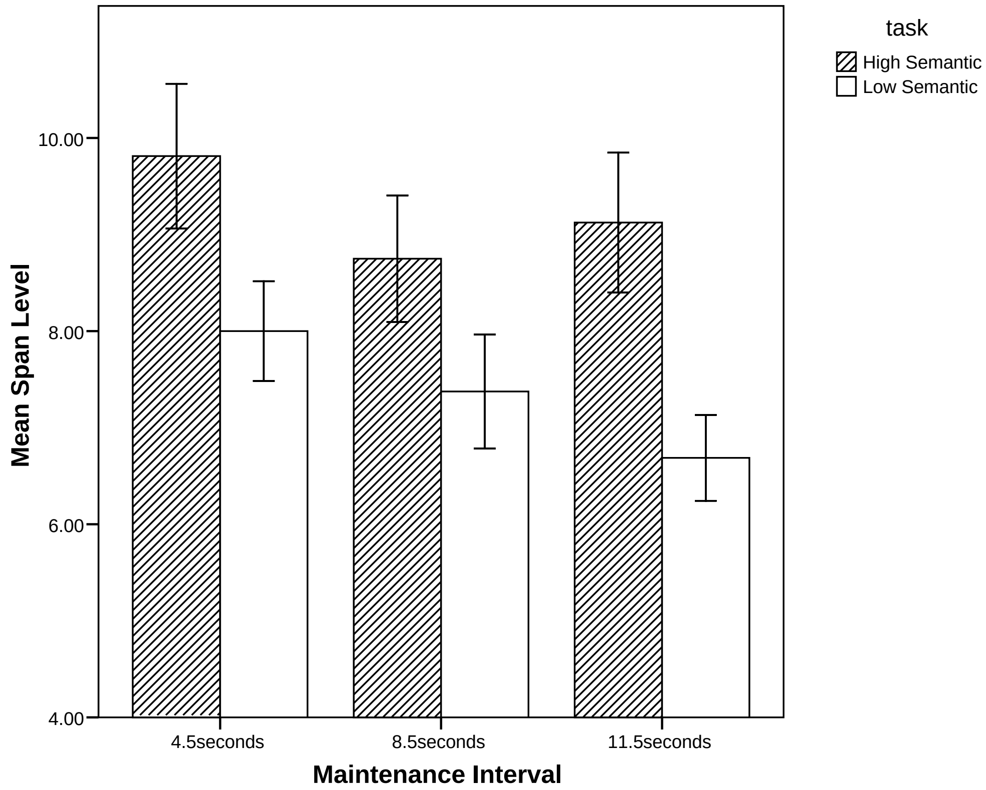


Figure 8.3. Graph of mean span level for the two forms of matrix pattern task under interference by DVN, presented across three maintenance intervals with standard error bars (+/- 1 SE)

8.13.2. Analysis of Maintenance Interval

The effect of increasing maintenance interval on the individual tasks was assessed using one way repeated measures ANOVAs for each task.

Size JND

The JND also showed a significant main effect of maintenance interval $F_{(2,30)}$ = 13.125, p <.001 η_p^2 = . 467, this showing the same pattern as the previous studies, 4.5s showed a higher performance than 8.5 (p = .005) and 11.5seconds (p<.001) but no difference between the two longer intervals (p = 1.000).

Low Semantic Matrices

Following Bonferroni correction there was a significant effect of maintenance interval for the low semantic task, $F_{(2,30)}$ = 9.603, p = .003 η_p^2 = .390. Bonferroni post hoc comparisons revealed that the only difference which reached significance was between 4.5s and 11.5seconds (p< .001).

High Semantic Matrices

The high semantic task showed no significant main effect of maintenance interval $F_{(2, 30)}$ = 3.867, p = .096 η_p^2 = .205.

8.13.3. Analysis of Z Scores

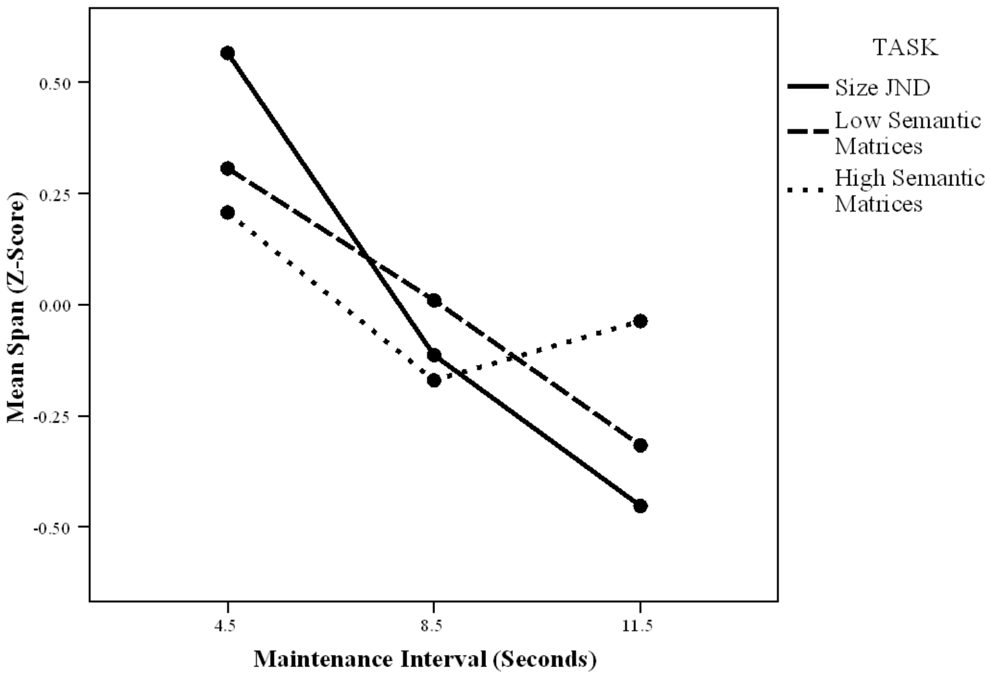


Figure 8.4. Graph Representing mean span (Z-score) for the JND and both forms of matrices at each of three maintenance intervals, under interference by DVN (1500ms presentation time).

To compare across tasks participants span level were standardised and a 3 (Task) x 3 (maintenance interval) mixed ANOVA was conducted. This revealed a significant main effect of maintenance interval ($F_{(2,90)}$ = 23.579, p <.001 η_p^2 = .344) and a significant interaction, $F_{(4, 90)}$ = 3.283, p = .015 η_p^2 = .127.

8.13.4. Comparison with Experiment 2

Size JND

Comparison between experiment 2 (no interference) and the present study shows a significant difference on the JND in terms of overall performance ($F_{(1, 34)}$ = 8.792, p = .005 η_p^2 = .205), with performance in the control version of the task (mean span = 21% change) being significantly better than performance under DVN interference (mean span = 26.04% change). There was, however, no interaction (F < 1), suggesting an identical pattern of decay across the two tasks.

Low Semantic Matrices

For the low semantic task there was no significant difference in terms of overall span level achieved following Bonferroni correction ($F_{(1,32)}$ = 3.346, p = .077 η_p^2 = .095), but a significant interaction ($F_{(2, 64)}$ = 3.222, p = .046 η_p^2 =.091). This can be attributed to a difference on between control and DVN at 4.5s (p = .034) and 11.5s (p = .038) but not at 8.5s (p = .451).

High Semantic Matrices

Finally, for the high semantic patterns there was no significant difference in performance between the two studies F< 1) and no interaction $F_{(2, 64)}$ = 1.013, p = .369.

8.14. Experiment 9: Discussion

Firstly, as predicted DVN had a small yet significant detrimental effect on the Size JND task and the effect size observed is consistent with literature employing DVN (Dean et al, 2008). This Supports the notion of DVN having its impact on a visual short term memory where precise visual detail is retained, therefore suggesting the squares in the JND task being represented online in a visual modality.

For the low semantic patterns, the effect of DVN was not significant following Bonferroni correction but there was a significant interaction when compared to control performance. This interaction was shown to be due to the impact of DVN being significant at 4.5s and 11.5seconds. The lack of an effect at 8.5seconds can perhaps be due to the power of the study and it could be predicted that this effect would be significant were further data collected. Nevertheless, this suggests that the low semantic patterns are dependent on a visual representation, as suggested by the devastating effect of a visually similar pattern interpolated between study and test in experiment 5. Although the effect of DVN is small, this is typical of studies employing this methodology (e.g. Dean et al, 2008; McConnell & Quinn, 2004).

Finally, for the high semantic patterns, there was no significant effect of DVN, suggesting that the representation held of the high semantic patterns does not necessarily need an online visual representation. It seems plausible that the visual information that can be stored offline and the categorical information is enough to maintain a representation sufficient to withstand interference with conscious visualisation and allow accurate change detection performance.

Several authors have argued that the effects of DVN are unlikely to be acting on LTM or retrieval from LTM because of the unstructured nature of DVN (e.g. Andrade et al, 2002; McConnell & Quinn, 2004; Dean et al, 2008). The present study serves to support this notion, with a differential effect of the DVN on the low and high semantic matrices. This along with the results of the 2-back procedure employed in study 5 of the previous chapter suggests that the high semantic matrices can be held in memory without the need for precise pre-categorical visual detail.

8.15. General Discussion

The present chapter has provided insight into the apparent equivalent executive demands made by both forms of matrix pattern. When attention is captured constantly by the continuous operation task (Lepine et al, 2006) performance on the two forms of matrix pattern task is equivalent. This level of performance is the same as seen on both forms of matrix task in the 1-back procedure employed in the previous chapter. This supports the tentative suggestion made in section 7.10, by which this size of matrix pattern (span level of 6 +/- 1) is the largest size that can be maintained in a visual modality when either the access or binding to categorical information is denied by placing demands on executive resources.

Regarding the high semantic matrix patterns, they appear to be sensitive to verbal (IS) but not visual interference (DVN). It is possible that the familiar forms present in the patterns are kept activated by rehearsal in phonological short term or working memory. The fact that DVN did not interfere with performance taken along with the lack of an effect of the intervening visual interference in the 2-back procedure, suggests that precise online visual information is perhaps not necessary for accurate change detection performance.

In contrast, the low semantic matrix patterns were affected by the introduction of DVN in the maintenance interval. This suggests that unlike the high semantic matrices, the maintenance of visual detail is beneficial to performance on this task.

The JND was impaired by DVN as predicted. This supports the literature suggesting that DVN interferes with the maintenance of fine visual detail and confirms that the effect of DVN on the low semantic matrices is in fact due to it interfering at the level of visual detail. Interestingly, the attentional interference task impaired performance on the JND to a level similar to that seen by the impact of the 2-back procedure. It is possible that participants need to attend to the stimulus in memory in order to retain a high fidelity representation (e.g. Olsson & Poom, 1995). When attention is occupied; the fine visual detail for size is lost. Finally, the IS did not have a significant effect on the JND task. However, there was a trend towards a detrimental effect at the longest maintenance interval. It is tentatively suggested that in the condition with 11.5second maintenance interval, participants only retain a rather coarse representation of size which is aided by a verbal code. This would be consistent with participants being able to perform the JND in the face of visual interference in the 2-back procedure. Further research would be necessary to ascertain whether the representation held in the JND fundamentally differs as a function of maintenance interval. If so, it is possible that this effect would then be eliminated if participants were unable to predict the duration of maintenance, perhaps by employing a randomised design.

8.16. Chapter Summary

The present chapter firstly employed attentional interference and replicated the impact seen in experiment 6 of the previous chapter. It is suggested that performance levels seen are indicative of a maximum matrix size which can be maintained and encoded in the absence of executive resources for higher-level, *active*, chunking. The size JND task was also impaired by attentional interference, perhaps implicating its recruitment of visual attention in the maintenance of high fidelity visual detail. Interference by Irrelevant speech was shown to have its greatest impact on the high semantic matrices. This is interpreted as this task making use of phonological resources to rehearse semantic details. Finally, Dynamic Visual Noise was shown to impact both the JND and the low semantic matrices, confirming the assumption that both are reliant on the maintenance of fine co-ordinate visual detail (or visuospatial representation described by Avons and Phillips, 1987). The following chapter will discuss the implications these results have and what they can tell us (along with the results from the rest of the thesis) with regards to the nature of the representations of the three tasks in working memory.

CHAPTER 9

General Discussion

9.1. Chapter Overview

The series of experiments reported in this thesis examined the nature of forming and maintaining multiple representations of a single stimulus in visual working memory. The initial three chapters discussed how current models of working memory can accommodate this phenomenon. The present chapter will now review how the models presented in the literature review for this chapter can accommodate the findings presented in the thesis. Firstly, a summary of the findings of the present thesis is given. The findings relating to the three major tasks used in the thesis (namely, the high and low semantic matrix task and the Size JND) are then discussed in turn in relation to the working memory models presented in chapters 1 - 3. Finally there will be a discussion of methodological constraints in the thesis, directions of future work and general conclusions that can be drawn.

9.2. Summary of Results

In this section a brief review of the findings from the current thesis is given. Since the thesis is concerned with the effects of maintenance interval, semantics and the manipulation of protocol, Table 9.1 summarises the span level and the significance of these three factors across the 8 studies (see graphical representation of mean performance in Appendix C). Experiment 1 is omitted from this table as it does not employ comparable tasks but will be discussed in this section.

Table 9.1. Summary of results for Experiments 2 - 9 in the present thesis. Results are broken down by task (JND, Low Semantic and High Semantic Matrices), by Maintenance Interval (4.5, 8.5 and 11.5seconds) and by main effect (Effect of maintenance interval, effect of semantic manipulation (not for JND) and a comparison with the results of Experiment 2 where relevant. Group means are also provided for each condition.

	JND			Low Semantic Matrices			High Semantic Matrices		
	4.5	8.5	11.5	4.5	8.5	11.5	4.5	8.5	11.5
Experiment 2: Control	17.00	23.00	23.00	9.66	7.94	8.16	9.72	9.50	9.56
Effect of Maintenance Interval	p=.033			P<.001			NS		
Effect of Semantics				NS					
Experiment 3: Replication	18.31	22.95	26.68	8.20	7.24	7.13	8.00	8.16	8.03
Effect of Maintenance Interval	p=.002			P<.001			NS		
Effect of Semantics				NS					
Different from Control	NS			NS			p=.008		
Experiment 4: Short Encoding	18.75	22.50	24.38	8.00	6.63	6.31	8.88	7.50	7.31
Effect of Maintenance Interval	NS			P<.001			p=.004		
Effect of Semantics				NS					
Different from Control	NS			p=.013			p=.003		
Experiment 5: 2-Back	31.33	36.00	38.00	x	x	x	5.56	4.94	4.88
Effect of Maintenance Interval	p=.004			x			p=.001		
Effect of Semantics				x					
Different from Control	P<.001			x			P<.001		
Experiment 6: 1-Back	15.00	21.25	24.38	6.28	5.36	5.29	5.93	5.53	5.53
Effect of Maintenance Interval	P<.001			p=.010			NS		
Effect of Semantics				NS					
Different from Control	P<.001			P<.001			P<.001		
Experiment 7: Attentional Interference	28.33	30.00	31.67	5.53	5.13	5.27	5.83	5.58	5.50
Effect of Maintenance Interval	NS			NS			NS		
Effect of Semantics				NS					
Different from Control	p<.001			p<.001			p<.001		
Experiment 8: Irrelevant Speech	15.31	20.31	25.94	8.20	7.67	7.13	10.07	8.92	9.07
Effect of Maintenance Interval	P<.001			NS			p=.006		
Effect of Semantics				P=.040					
Different from Control	NS			NS			NS		
Experiment 9: DVN	21.88	26.88	29.38	8.00	7.38	6.69	9.81	8.75	9.13
Effect of Maintenance Interval	p<.001			p=.003			NS		
Effect of Semantics				p=.037					
Different from Control	p=.005			p=.046			NS		

9.2.1. Experiment 1

Experiment 1 served to confirm that the executive involvement in the visual matrix pattern task is comparable in magnitude to the Corsi blocks task, which is known to place significant demands upon executive resources (e.g. Rudkin et al, 2007). It was also designed to show that the Size JND task is relatively free of executive demands in comparison to the Corsi and matrix pattern tasks. To investigate this, three executive tasks were used which each made two types of executive demand, an executive demand *specific* to that task (e.g. updating, Shifting or Inhibition) and a *general* executive demand, common across the three tasks. The purpose of doing this was to highlight the domain-general nature of the executive interference (e.g. Bourke et al, 1996; Miyake et al, 2000).

The data from Experiment 1 supported the initial hypotheses. The Size JND task was relatively robust to executive interference when compared to the matrix patterns and the Corsi which were shown to be equivalently affected by secondary interference. Further to this, the only factor affecting the size of the impact of the secondary tasks was the amount of cognitive effort the executive task captured (cf. Barrouillet et al, 2004). The nature of the executive involvement in the matrix patterns task was discussed and one overriding theory in the literature regarding this views the involvement of semantic resources in memory for visual matrix patterns (e.g. Avons & Phillips, 1987).

9.2.2. Semantic Classification of Matrices

All subsequent studies in the thesis were then concerned with differences in high and low semantic forms of the visual matrix patterns task, both relative to each other and to the Size JND task, used as a benchmark for visual STM performance. A classification study was carried out and reported in chapter 5. This involved participants rating a large set of visual patterns in terms of their semantic affordance, and two subsets of patterns were then selected. One which lends itself to semantic support and one which does so to a lesser extent. It was then demonstrated that these two pattern sets differed from each other significantly in their ratings of semantics at every level of complexity. Finally, internal consistency of the two pattern sets was tested and both sets were shown to be highly reliable.

9.2.3. Experiment 2, 3 and 4

Experiment 2 was carried out to investigate the stability of the memory representations in the Size JND and the two forms of matrix pattern task across increasing maintenance intervals. To do this, a recognition format of the tasks was created and participants were taken to their individual span level at each of three maintenance intervals. It was shown that for the low semantic matrices and the Size JND, there was significant drop in performance across increasing maintenance duration. This effect was not present in the high semantic matrices, the representation of which appears to remain stable across maintenance intervals (up to 11.5seconds). This was discussed in terms of stability of representations in categorical and pre-categorical form.

Experiment 3 aimed to replicate the effects of experiment 2 when task administration was randomised rather than blocked by maintenance interval. This replication was successfully achieved. However, lower performance was observed in the high semantic matrix tasks when randomised compared to blocked, potentially due to fatigue effects caused by the longer protocol. From this point on in the thesis, a blocked design was used to avoid fatigue and the results of Experiment 2 were employed as a reference for baseline performance on the tasks in the absence of any interference.

Although the only systematic difference between the two forms of matrix pattern is the degree to which they afford semantic representation, this needed to be substaintiated. Curby and Gauthier (2007) suggest encoding time must be sufficient to allow for full semantic elaboration. As such Experiment 4 was designed to limit encoding time, with the hypothesis that this would result in less semantic information being encoded and thus lower overall performance and reduced stability over increasing maintenance intervals. This was confirmed; both the high and low semantic matrix tasks showed a reduction in performance suggesting both rely on semantic support to some extent. Importantly, the high semantic matrix task now showed significant decay across the three maintenance intervals, suggesting its stability in studies 2 and 3 was indeed a function of the increased semantic support during encoding. Interestingly, the Size JND was unaffected by this manipulation, suggesting 500msec encoding time was enough to encode the stimulus and there was no advantage of this increasing to 1500msec.

9.2.4. Experiments 5 and 6

Following the characterisation of the tasks' decay functions and the confirmation of increased semantic support in the high semantic task, the thesis turned to investigating executive and the broader working memory processes involved in the tasks. Research on the executive involvement in the binding of short and long-term semantic visual representations is lacking in the literature. Further to this, research investigating short and long-term binding in the verbal domain is inconclusive with regards to executive involvement (e.g. Allen et al, 2009; Allen et al, 2006; Jeffries et al, 2004).

A further point of interest was to establish the tasks' reliance upon visual resources, this was achieved in Experiment 5 by employing all three tasks in a 2-back procedure. This procedure recruits executive resources in the updating of the contents of working memory and visual interference by the intervening pattern. This leads to a reliance on the pattern being represented in long term visual memory, where the representation may be immune to visual interference. Phillips and Christie's (1977a) characteristic one-item recency effect in serial memory for visual matrices was shown to be eliminated by subsequent visual stimulus, with pre-recency items being maintained at a lower but above-chance level. Several authors attribute performance on the pre-recency items to categorical representation of the stimulus (e.g. Avons & Phillips, 1987; Walker et al, 1993). Therefore, it was predicted that the low semantic patterns would show a greater impact of being forced 'offline'. This was confirmed. Participants were unable to complete the low semantic matrix pattern task when visual and executive resources were denied in the 2-back protocol yet maintained above chance performance on the high semantic task. In this task, participants are unable to employ executive resources to aid chunking of the pattern, yet in the high semantic condition, they are able to represent the patterns and in the low-semantic condition they are unable to do so. It is possible that participants represent the high semantic patterns in a verbal modality. Parts of the high semantic pattern may lend themselves to being represented as verbal labels without eliciting executive support, and this would suggest chunking of this sort to be relatively automatic. As such the subsequent studies aimed to examine this.

Using the 2-back procedure created the added interference effect of having an intervening visual stimulus between study and test. A further study (Experiment 6) was carried out in which the three tasks were employed in a 1-back procedure, requiring participants to respond if the stimulus on screen is the same as the one immediately beforehand (thereby eliminating visual interference). When this was performed there was no overall change in the high semantic task relative to the 2-back procedure, suggesting there was no additional effect of the visual interference in the 2-back procedure. Participants were now able to perform the low semantic matrix task at a level equivalent to the high semantic matrices. This was discussed in terms of a pattern representation, dependent on visual support that represents the maximum size visual pattern which could be remembered when access to executive resources is denied. Interestingly, there was no effect of the 1-back procedure on the Size JND, suggesting the large effect observed in the 2-back task was caused by only the visual interference. Again, this provides support for the Size JND being relatively free of executive demands.

9.2.5. Experiments 7, 8 and 9

Studies 5 and 6 did not differentiate between executive interference in encoding, maintenance and retrieval. Furthermore, the studies presented thus far in the thesis have not explicitly tested the impact of discrete visual, executive or verbal interference. As such the final empirical chapter (Chapter 8) was initially concerned with employing executive interference in the maintenance period only, and then went on to employ visual and verbal interference paradigms. Experiment 1 showed that when performing at span level, executive interference did have an effect on performance of the Size JND task. It was suggested that this represents the need for sustained attention to the stimulus in memory to preserve high-resolution size detail. As such the executive interference employed in Experiment 7 was one which continually captured attention. For the Size JND, a large drop in performance was seen. This was taken as being indicative of the need for continued attention to the Size JND stimulus to preserve size detail with precision. It was shown that the attentionally demanding secondary task severely impaired performance on the two forms of matrix pattern task, leaving performance levels equivalent to those seen for the high semantic patterns in experiment 6. Again, this was interpreted in terms of the maximum size pattern that can be remembered in the absence of executive support.

The final two studies in the thesis were concerned with identifying the slave systems involved in the maintenance of the three tasks. Firstly irrelevant speech was employed and it was demonstrated that this had its effect on the high semantic Matrices. This effect was proposed to provide support for a multi-modal representation of the matrix patterns - it is possible that the semantic labels given to pattern elements can be rehearsed in verbal working memory. This would account for the above chance performance of this task under 2-back interference where access to executive and visuospatial resources is compromised. The final study employed Dynamic Visual Noise (DVN) in the maintenance period; this was shown to have a significant negative impact on the Size JND suggesting both are accessing short-term visual memory. Further to this, DVN had a significant effect on the low semantic matrices. This supports the suggestion made in Studies 5 and 6 that the low semantic matrices are also represented in, or dependent upon, visual STM. However, there was no effect of DVN on the high semantic matrices, perhaps suggesting its reliance on semantic memory is much greater than the low semantic matrices.

9.3. The Functional Architecture Underpinning Multiple Representations

This section will discuss the findings for each of the three major tasks employed in the thesis in turn. The findings of each task will be discussed in relation to models of working memory introduced in chapters 1, 2 and 3.

9.3.1. Size JND Performance

Firstly, the results for the Size JND will be considered. Although employed as a benchmark for visual STM, the Size JND has produced results that have interesting theoretical implications. Firstly, In Experiment 1 it was shown that the Size JND makes significantly fewer demands on *general* executive resources relative to the matrix patterns task and the Corsi task. However, the impact of general executive interference was significant for the Size JND throughout the thesis. As such, a first point to consider is the nature of these executive demands.

In Cowan's (2005) model of working memory it is suggested that continued attention to a stimulus can keep it activated, when attention is withdrawn from the maintenance of the representation it will decay. As such it is proposed that the executive interference observed with the Size JND is due to the need for attention to maintain the fine size detail. This is confirmed in Experiment 7, when the continuous operation task is employed thereby occupying attention constantly (Lepine et al, 2006) performance on the Size JND drops significantly. Pearson (2001) proposes that representations in the visual buffer will decay in the absence of the central executive (employed to refresh the representation), therefore these results can be interpreted readily within both Cowan's and Pearson's models.

When the executive demands made are such that attention is only occupied briefly, as in the 1-back version of the Size JND (performed in experiment 6), there is no effect on performance. This suggests that the interference seen in Experiments 1 and 7 is not a result of specific executive demands but is more closely related to the need for *sustained* attention in the maintenance of high-resolution size information.

Cowan (2005) proposes that there is potentially no time limit to working memory representations in the focus of attention, implying that when a person can constantly attend to a stimulus there should be no decay other than that associated with reduced vigilance. However, in experiments 2 and 3 of the present thesis, despite participants being able to fully attend to the square, resolution for size decayed significantly over the course of the first 8.5seconds, to a level of performance indicative of a categorical representation. This is not readily accommodated in Cowan model. As such, the results may be better represented in a system such as Pearson's (2001) or Kosslyn's (2006) Visual Buffer. Pearson (2001) specifies that the visual buffer is subject to rapid decay which can be reduced but not eliminated with executive involvement (either via the CE, in the case of Pearson or via the attention window in Kosslyn, 2006). This is supported by experiment 7, where attention is occupied by the continuous operation task, performance drops to the level of a categorical representation for size within the first 4.5seconds of maintenance. Under control conditions, this level of representation only occurs at

8.5seconds; suggesting attention to the stimulus reduced but did not eliminate decay.

The encoding time manipulation in Experiment 4 had no effect on the Size JND. The reduction of encoding time to 500msec is perhaps insufficient to impact task performance. This is consistent with the work of Vogel et al (2006) suggesting that a single item's worth of information can be encoded into visual short term memory within 50msec. It is also possible that this could further explain why the Size JND was unaffected by the 1-back manipulation. During the 1500msec presentation time participants must compare the present stimuli with the previous one and encode it sufficiently to survive until test. If encoding occurs within the first 500msec, then this would explain why switching attention from encoding to processing of the task did not impact performance. This also provides support for Barrouillet et al (2004) TBRS model, discussed in chapter 2.

The impact of the 2-back task can therefore be attributed to visual interference. This would suggest that the system responsible for maintaining the squares is one which is subject to displacement by subsequent stimuli. This is consistent with the square being consciously imaged in a system such as a visual buffer, which is thought to be limited in capacity (Pearson, 2006). In experiment 9, Dynamic Visual Noise (DVN) had a significant negative impact on performance of the Size JND. DVN has been shown to have an impact largely on tasks requiring imagery (e.g. McConnell & Quinn, 2000; 2004; Quinn & McConnell, 1996a, 1999; Smyth & Waller, 1998). Several authors have suggested DVN may actually be having its impact on retrieval from LTM. The fact that DVN didn't affect the high semantic patterns goes against this and provides further support for the JND stimulus being represented in the temporary visual representation. This again, implicates an online memory system such as Pearson's visual buffer.

Finally, there was no impact of irrelevant speech (IS), supporting the notion of the Size JND being a relatively pure measure of visual short-term memory. This is also consistent with McConnell and Quinn (2004) who observed no impact of IS on a task very similar in nature to the Size JND. However, at longer maintenance intervals (i.e. after 8.5seconds), where the representation is at the size that could be represented categorically, interference by IS approaches significance. At this level participants are able to detect around a 30% change in size, and therefore it is possible that the number of verbal labels needed to achieve this would be within the 7 chunk-capacity of working memory hypothesised by Miller (1956). Further investigation is needed to confirm this but it suggests that the Size JND may be eliciting dual-representation hypothesised to play a large role in performance of the matrix tasks (e.g. Avons & Phillips, 1987; Ichikawa, 1985; Phillips & Christie, 1977a; b). This implicates models of working memory which specify information entering working memory via LTM (e.g. Logie, 2003) or activated LTM models (e.g. Cowan, 2005), as the categorical representation of size observed is present even in a randomised design (Experiment 3) where participants cannot pick a strategy on the basis of maintenance interval.

In summary, the Size JND appears to be encoded very rapidly in visual STM (less than 500msec), represented in a temporary visual memory system and maintained with continuous attention to the representation. This representation is sensitive to irrelevant visual interference and subject to rapid decay (over 8.5seconds) and appears to plateau at this point. It is suggested that at this point, the mean change in size that can be detected is indicative of a change is size that can be represented categorically or verbally. It is further predicted that at these levels of performance, interference by irrelevant verbal material may well impair performance.

Initially, the most obvious model to accommodate these results, because of its specification of activated LTM and continued attention, is Cowan's embedded processes model (see section 2.3 for a review). In this model it is suggested that representations of the square are held in the focus of attention, when attention is occupied the representation enters STM and decays more rapidly. However, this would also suggest that the focus of attention is time limited where semantic support isn't readily available. This goes against the description of the focus of attention given by Cowan (2005). A suggestion made by Cowan (personal communication, August 18th 2009) is that the verbal representation of the square outlasts the visual representation, proposed to be a sensory representation which decays, even in the focus of attention. This would suggest that the Size JND task is perhaps more closely associated with *sensory* or STM rather than *working memory.*

These results also lend support for Pearson's (2001; 2006, described in section 1.3.4) model where information which requires high resolution is stored online in the visual buffer and refreshed by the central executive. This central executive involvement could be in the form of attention and serves to *reduce* (not eliminate) decay. Representations in the visual buffer are subject to displacement by intervening stimuli (as observed in Phillips & Christie, 1977b), in such a case the representation may be shunted 'offline' into the visual cache and represented more coarsely and subject to a more rapid loss in fidelity. A categorical representation may also be formed and rehearsed in the phonological loop. Given the possibility for multiple representations, it is necessary to understand the mechanisms for integrating across modalities. The main criticism of Pearson's model arising from the present thesis is that it does not sufficiently describe the mechanisms by which this integration is achieved.

However, Baddeley (2000) proposes the Episodic Buffer (discussed in section 1.3.5) to be responsible for binding information in a multi-dimensional code. In this model, visual representations can be stored in the VSSP and refreshed via the central executive. Such a system would be susceptible to interference by DVN, it is possible that the Size JND representation is maintained in the VSSP, where the representation would decay over increasing maintenance intervals. The verbal or categorical labels for size could then be maintained passively in either the phonological loop or episodic buffer.

9.3.2. Low Semantic Matrices Performance

The next task which will be considered is the low semantic matrices. This task was created to reduce the opportunity for semantic support. A first observation is that, under conditions of no interference, performance on this task is akin to the Size JND. Specifically, it is subject to rapid decay across the first 8.5seconds. This immediately suggests that the matrices may be *maintained* in the same system as the JND stimulus.

In contrast to the JND, performance on the low semantic matrices is impaired by a reduction in encoding time from 1500msec to 500msec. This suggests that *encoding* of the matrix is not equivalent to the JND, this is consistent with the matrices activating some elements of semantic memory. When STM capacity is exceeded (as in the span procedure) executive resources are engaged to allow for chunking of information on the basis of semantic information (e.g. Jeffries et al, 2004). Although this allows for improved memory performance in the 1500msec encoding condition, this semantic elaboration is not sufficient to create a stable representation as it does in the high semantic task. However, the level of performance seen is still greater than that observed under executive interference, supporting the idea of some executively driven semantic elaboration. This supports a model whereby visual information and semantic information may be activated concurrently.

When performed as a 2-back task, it would be expected that the intervening stimulus would impair the visual representation (e.g. Della Sala et al, 1999). When visual capacity is exceeded participants should recruit executive resources to chunk information on the basis of semantic information. However, the 2-back procedure also denies the opportunity to recruit executive resources which are used in the aid of semantic elaboration (e.g. Jeffries et al, 2004). Under such conditions, participants are unable to represent the patterns and cannot perform the task, even at an entry level of 4. This suggests that any semantic representation that can be formed of the low-semantic visual patterns, is one which requires executive resources. Allen et al (2009) propose that representations in the Episodic Buffer may be bound by either ambient (automatic) or focussed (executively demanding) attention. It may be that the binding of information (during encoding) required for the low semantic patterns, where the semantic links are not as rich, recruits focussed attention which is demanding of executive resources.

When the intervening visual stimulus is removed in the 1-back procedure (Experiment 6), performance is severely impaired relative to control but participants are able to perform the task. However, given that access to executive resources is compromised, it is proposed that this level of performance represents the maximum capacity of the temporary visual system employed defined by only quantitative complexity (cf. Ichikawa, 1985). Ichikawa's definition of quantitative complexity was proposed to be defined by properties of the stimulus such as overall number of cells and certain types of gestalt property such as continuity. This type of complexity may be representative of pattern properties which can be chunked automatically. Baddeley (2007) proposes that executive resources are employed to increase capacity when slave system capacity is exceeded in verbal working memory. It stands to reason that the same process could take place in visual working memory. In Experiment 6, where access to executive resources are denied the representation that is held in memory is representative of the capacity of a temporary visual memory representation, this could explain why there is a significant decay function. Performance on the low semantic under 1-back interference decays between 4.5 and 8.5 seconds, at which point it is equivalent to the high semantic matrices. It may be that a visual representation is formed, as in the Size JND but this representation is stored ‘offline’ due to the executive interference and as such begin to decay. This would suggest the performance levels seen in experiment 6 on both the high and low semantic tasks are representative of the capacity of offline or unattended short term memory. It is possible in the high semantic patterns that this involves a verbal short term memory (as suggested by experiment 5) to maintain automatically chunked items.

The above suggestion is supported by the results of experiment 7, where attention is continually occupied during maintenance by the secondary task employed. Under such conditions task performance is equivalent to the 1-back task. Again, suggesting a maximum capacity of visual memory without executively driven chunking or support. This does however also suggest that the maintenance of the low semantic matrices is not dependent on *sustained* attention as the JND is. Continually capturing attention in experiment 7 is no more detrimental to span than the 1 back in experiment 6 where executive resources are employed only to update the contents of working memory.

As discussed above this could perhaps implicate the function of another visual memory system, and it was proposed that the Size JND is maintained online in a visual buffer (see Pearson, 2001), in the VSSP (see Baddeley, 2000) or within the focus of attention (see Cowan, 2005). It may be that in the absence of executive support for additional semantic elaboration (experiment 6), and when attention is occupied continually (experiment 7), the low semantic Matrices are stored in a different system or by different mechanisms to the Size JND. Perhaps the patterns are chunked automatically and held in an offline or passive store. For example, Pearson’s Visual Cache, Baddeley’s episodic buffer or outside of the focus of attention in Cowan’s model.

Cowan (personal communication, August 18, 2009) proposes that the JND is maintained as a form of sensory memory. It may be that the low semantic matrices represent a different form of memory, perhaps activated LTM and are able to temporarily leave the focus of attention and be maintained in short term memory. Cowan (1988) proposed short term memory may contain a later sensory memory, which contains information that is partially interpreted but that is dependent on the sensory information and subject to rapid decay (Conway et al, 2001). This could be the system responsible for the maintenance of the JND. A second possible explanation is that this represents the function of an offline memory system such as Pearson's (2001) visual cache, which may contain information that is partially interpreted but that is stored without the need for attention (Pearson, 2006).

It was shown that verbal interference had no effect on the low semantic matrices in experiment 8. It is possible that the type of semantic support that is available in the low semantic matrices is not linked with a verbal STM representation; perhaps the semantic representation in this task is visual in nature, and driven by automatic processes but recruits executive resources to elaborate the representation on the basis of more abstract semantics. It is also possible that some verbal labelling of the low semantic patterns occurs, but that these labels are not necessary to facilitate performance.

DVN was shown to have a significant effect on the low semantic matrices in experiment 9. For the JND this was interpreted as interference caused by competition for the visual buffer. It may be that the matrices are stored online in the visual buffer to maintain high resolution representations or in the focus of attention. In the face of interference, it is possible that the representations can be shunted 'offline' into a visual cache or outside of the focus of attention. The drop in performance under interference by DVN, may represent the change in the quality of the representation between online and offline representation of the matrices. In Cowan's model, attention may be recruited by the central executive or it may be captured by changes in the environment (Cowan, 1988). DVN may act on the latter by changing the focus of attention long enough to produce decay in 'online' visual representations.

Awh et al (2007) showed that the number of representations and the resolution of the representations of a stimulus in visual working memory are not correlated, suggesting these are separable processes. They went on to show that capacity is constrained by the resolution of representations when the differences between sample and test stimuli are small and within-category. As sample-test similarity decreased, performance is less dependent on resolution. In the high semantic patterns, it is possible that the differences between sample and test stimuli are larger than in the low semantic patterns. If this is so, it may be that the low semantic patterns are more reliant on resolution and as such need to be represented in or refreshed by a similar system to the JND stimulus. It is likely that this is an online system, such as the visual buffer, VSSP or the focus of attention.

It was shown in Experiment 4 that a reduction in encoding time (and therefore a reduction in the opportunity for semantic elaboration) has an effect on the low semantic matrices. As such it may be that the 'offline' representation is indicative of semantic representation of the matrix, which is less reliant on the high-resolution visual detail. This would also explain why DVN affected both the low semantic matrices and the JND to a greater extent than the high semantic matrices, as the latter are more able to rely on a richer LTM semantic representation when forced into offline representation.

In conclusion, the low semantic Matrices show clear evidence of activating some elements of LTM, again supporting a model where information passes through LTM or where working memory is activated LTM. The low semantic matrices, under no interference, appear to rely on the same mechanism as the JND, one which is susceptible to interference by DVN, requires attention and decays rapidly. However, 1-back executive interference and strong attentional capture have an equivalent impact on the low semantic matrices, suggesting the matrices can perhaps be represented offline more efficiently than the JND. This is thought to be representative of the matrices affording more semantic representation. Under interference by attention and 1-back interference, the offline representation may rely on LTM activation without attention. Cowan proposes this is possible, but that this activation will only be partial. The greater reliance on attentional resources in the JND supports the possibility for the low semantic matrices being represented as activated LTM, (e.g. Cowan, 1988; Phillips, 1974) and the JND stimulus being represented in sensory memory. This could also represent storage in the visual cache in Pearson's (2001) model, which is stored separately from executive resources. A further possibility is one suggested by Allen et al (2009) where attention can be classified as ambient or focussed, and it is proposed that the episodic buffer can also be employed to store information via ambient attention, which is not dependant on executive resources. It may be that the partial semantic elaboration of the patterns under interference is due to this process, this will be discussed in greater detail below.

9.3.3. High Semantic Matrices Performance

The final task to be considered is the high semantic matrices. The results associated with this task bare some striking contrasts to the two tasks discussed above. Firstly, in contrast to the other tasks, the high semantic matrices show no decay over periods of up to 11.5seconds under control conditions. This lends support for research suggesting that the integration of rich semantic information increases the stability of a representation (e.g. Conway et al, 2001). When encoding time is reduced to 500msec from 1500msec in Experiment 4, it was shown that overall performance is negatively affected and there is an increase in decay, suggesting a decrease in the stability of the representation. This supports research proposing that the integration of semantic information increases the time required for rich encoding (e.g. Curby & Gauthier, 2007).

A further contrast to the previous studies is the impact of irrelevant speech on high semantic matrix performance. When the task was performed with irrelevant speech in the maintenance interval, there is an increase in the decay function associated with the task. As irrelevant speech has been shown to impact on verbal memory (Salamé & Baddeley, 1982), this implicates the stimulus being held in a verbal modality, and would suggest that one of the systems scaffolding performance and increasing stability is a verbal temporary memory.

This also has implications for the results of the 2-back task. In contrast to the low semantic matrices, participants could perform this task as a 2-back. Given that this representation is unlikely to be visual in nature as there is an intervening visual stimulus (e.g. Della Sala et al, 1999) and the access to semantics is denied through the executive demands. It seems plausible that performance may be maintained through a temporary verbal representation or a passive episodic buffer process.

As discussed above Allen et al (2009) propose that the episodic buffer may be able to function in the absence of executive resources. It is possible that under interference by 2-back the patterns may activate some verbal semantics where patterns contain familiar forms such as letters, and that these can be maintained in a verbal code, therefore making them susceptible to interference by IS. The fact that interference occurred with IS in the absence of visual or executive interference, suggests that this verbal coding occurs during normal task performance and not just when other memory systems are compromised. This could have implications for the episodic buffer as cross-modal coding would be necessary and this is proposed to be a function of the episodic buffer (Baddeley, 2007). However, this can also be represented within Cowan’s model, where information from all modalities that is associated with a stimulus is activated concurrently and linked in activated memory.

For the low semantic matrices in the 1-back task there was slightly elevated performance at 4.5seconds relative to the high semantic task and the same task at the longer maintenance intervals. This could be due to the 1-back procedure’s effect on encoding time, by requiring encoding of the stimulus and processing of the task less of the presentation time (1500msec) could be dedicated to encoding. Experiment 4 demonstrated an effect of limiting encoding time on both the decay function and the overall performance on the high semantic task whereas the impact on the low semantic task was limited to a small change in overall performance. If the low semantic task dedicated less time to encoding, more attention may have been dedicated to comparison to the previous pattern leading to a slight increase in performance at the shortest maintenance interval.

For the high semantic matrices, performance on the 1-back is equivalent to the 2-back and the low semantic at the two later maintenance intervals. This is perhaps indicative of a performance level equivalent to the maximum capacity of offline visual memory in the absence of executive support, as suggested above for the low-semantic task. The same results were observed for the high semantic patterns in the attention task (experiment 7) as were observed for the low semantic task.

Performance was equivalent to both forms of n-back. This could suggest that *continued* attention to the stimulus is not necessary and that performance can be maintained offline and refreshed via attentional resources.

Finally, there is no significant effect of DVN. This is perhaps indicative of participants being able to maintain information in verbal working memory when access to visual working memory is compromised. Alternatively, the patterns could be represented in an episodic buffer with the semantic representation being immune to interference by DVN. The most obvious explanation of this is that DVN does not access a system that is *necessary* for performance of the high semantic matrices. The increase in semantic representation may reduce the need for online precise visual detail to be maintained. It is possible that an increase in semantic affordance in the patterns may result in a decrease of similarity between target and distracter patterns; this would reduce the need for a high-fidelity representation (e.g. Awh et al, 2007).

In conclusion, it appears that the representation held of the high semantic matrix pattern may be more complex than first thought and also have significant implications regarding the integration of multiple representations in working memory. It appears that several representations are formed of the matrix pattern. Firstly, the patterns are not proposed to be constantly maintained as an online visual representation, instead the patterns appear to be able to be maintained offline without the need for *continuous* attention with enough efficacy to maintain stability of the representation across increasing maintenance intervals. The impact of occupying attention would imply that attention or executive resources are perhaps employed to refresh the representation. The second representation is proposed to be semantic in nature, the increased encoding time associated with this task suggests that more associated representations are activated in LTM. The process of accessing and integrating the semantic representations is proposed to be executively demanding (e.g. Cowan, 2005), under normal conditions it is this type of semantic elaboration that is represented. When executive resources were compromised, the representation held was one which didn't make use of semantic representations activated consciously or effortfully (i.e. automatic chunking). A third representation is proposed to be held in verbal short term memory. This may be semantic information which is activated automatically and maintained in a verbal modality, and this would allow for the above-chance change detection performance observed in the 2-back procedure, where visual and executive resources are compromised. More salient units of semantic information may be activated automatically (Cowan, 1988) and when irrelevant speech is included as an interference task, performance suffers.

Finally, it must be discussed how the overall findings for the high semantic task can be incorporated into a model of working memory. The most necessary function of a model which can readily incorporate these results is that it must be able to explain the integration of multiple representations. Pearson's (2001) visual cache – visual buffer model, despite providing sufficient description of the previous tasks and one of the most detailed descriptions of visual short term storage and imagery, doesn't describe the integration of representations across modalities in sufficient detail.

One way to understand how integration in this model may occur is to look at Kosslyn's model of visual imagery. In Kosslyn's (2006) model, the high semantic matrix would enter the visual buffer (similar in nature to Pearson's visual buffer), where the stimulus doesn't match perfectly onto a representation in associative memory (similar to LTM), an attention shifting system turns the attention window (similar to the focus of attention) to a particular part of the stimulus such as an obvious chunk. This chunk is then passed through the system and activates associative memories and is kept active in a short term associate memory, the attention shifting system would then orient attention to another salient chunk and repeat the process. This would account for the increased encoding time with high semantic patterns as more chunks must be passed through the system. It is also possible that with an increase in activated elements in short term associative memory, there would be a decreased dependence on a conscious visual representation being held in the buffer. This would account for the lack of interference by DVN and also explain why the JND is more demanding of attention than the matrices. Both forms of matrices activate some elements of associative memory and as such can be maintained without constant attention to the stimulus in the visual buffer. A limitation of Kosslyn's (2006) model, is that it does not adequately specify links with verbal representations and as such it is unclear how IS would interact with the representations.

Two models described in the literature review of the present thesis that provide a description of the processes involved in integration of cross modal representations are Baddeley's (2000) Episodic Buffer model and Cowan's (2005) Embedded Processes model.

In the Baddeley (2000) model, visual representations could be held in the VSSP and refreshed via the central executive, semantic information would then be integrated through effortful processes in the Episodic Buffer which would recruit attention or executive resources to do so. However, in the present thesis in the absence of executive resources and attention some LTM information is activated automatically, as demonstrated by the studies involving executive interference. Baddeley's (2000) model does not describe a process for binding which operates away from the central executive. However, Baddeley et al (in press) make a substantial revision to the episodic buffer model.

Baddeley et al (in press, discussed in chapter 3) found that the superiority effect observed for sentences over word lists was not eliminated (or reduced) by a concurrent executively demanding task. They also found that both phonological and visuo-spatial interference impaired performance on both sentences and word lists, but that these did not eliminate or reduce the superiority effect for sentences. They conclude from this that the processes involved in the chunking of sentences are automatic with no additional dependence on the central executive. This is similar to the superiority observed for the high semantic patterns above the low semantic in the 2-back task (Experiment 5). As mentioned above, these results do not fit within a model where episodic buffer operation always implicates executive resources.

Baddeley et al (in press) go on to modify their account of the episodic buffer model, proposing that information is bound without the need for attention. Upon entering the episodic buffer, the chunks or episodes are available to attention but do not *necessarily* recruit it, suggesting the episodic buffer may contain chunks of information which are outside the focus of attention. The chunks may then be manipulated via focussed attention.

This account of a more *passive* episodic buffer which contains information which may then enter the focus of attention bares striking similarity to Cowan's (2005) model of working memory. In this model the high semantic patterns would enter working memory as a sensory representation and some salient parts of the pattern would activate associated semantic representations. The focus of attention is then directed to the stimulus voluntarily by the central executive, and this serves to activate further semantic representations and increase stability (Cowan et al, 1990). This process is also the process assumed to demand increased encoding time. When executive resources are occupied, this additional semantic support isn't available and performance is representative of the sensory representation and the most salient, automatically activated LTM representations. It may be that these salient, representations (such as parts of the pattern resembling letters) are represented in a verbal modality and it is these that are interfered with by irrelevant speech.

If DVN has its impact on the same system responsible for conscious visual imagery, it is likely that DVN is acting on the focus of attention. As discussed above, the focus of attention is proposed to be involved in voluntary activation of semantic features during encoding. Beyond encoding it may be that the representation does not require constant attention. The focus of attention is proposed to be captured automatically by changes in the visual field (Schvaneveldt et al, 1982), but it can then be redirected away consciously (Engle et al, 1995) or may be habituated to (Cowan, 1988). It may be that DVN has its impact by capturing attention and directing it away from maintenance of the representation but that it can then be directed back to the representation. This temporary redirection of the focus of attention is not detrimental to the high semantic patterns but does affect performance of the low semantic matrices.

9.4. Methodological Considerations and Directions for Future Research

Prior to drawing conclusions from the results and theoretical frameworks discussed above, this section of the discussion will consider methodological strengths and weaknesses of the thesis and possible areas to improve the methodology for future research. It will also consider directions for future research inspired by the findings in the present thesis.

9.4.1. General Considerations

Firstly, the use of a recognition version of the tasks has yielded interesting results; this methodology has been suggested as being more representative of the way in which visual working memory is employed in everyday cognition (Luck, 2009). visual scene are typically interrupted briefly by blinks and objects intersecting the scene. People must therefore compare their internal representation of the scene before the interruption and the current visual input to detect any significant changes. This is essentially the same mechanism employed in the recognition paradigm, and this ecological validity is therefore a strength of the present thesis. However, some advantages of the recall procedure will be discussed below.

A second general methodological strength is the use of the span procedure. A central focus of the present thesis has been concerned with the involvement of executive processes when the capacity of short term memory is exceeded. The span procedure allows for the gradual increase in mnemonic load until short term memory is exceeded and strategic processes can be employed to increase capacity to the participants' maximum span. Therefore this procedure controls for individual differences in span, and ensures working memory is always taxed according to this.

It must also be noted that the majority of participants were female. As there are known differences in ability between males and females in visuo-spatial abilities, specifically with regards to visual matrix patterns (Della Sala et al, 1997), it is possible that this could be a limiting factor in the extent to which the results can be generalised.

Although individual differences were controlled for by the use of a span procedure, these could prove to be interesting in their own right. One factor that is of particular interest is age. Presentation time has been shown to directly affect the stability of the representations in the present thesis; it is presumed that this is indicative of the amount of time needed for a participant to encode the stimulus. It seems plausible therefore that individual differences affected encoding time, such as processing speed, may directly affect span. Age is known to impact speed of processing (Hamilton et al, 2003); as such the effect of the semantic manipulation in children and older adults along with measures of processing speed, or perhaps limiting encoding duration in the same group, would be particularly interesting.

The involvement of executive and strategic processing was shown to be differentially important across the tasks, with a greater reliance on executive resources in the high semantic task due to its greater affordance for semantic elaboration. Executive resources have been shown to be more efficient in young adults with the developmental trajectory following an inverted U-shape (Baddeley, 1986; Phillips & Hamilton, 2001). As such it would be expected that the advantage for the high semantic matrix pattern would perhaps be eliminated or reduced in children and older adults.

9.4.2. The Size JND

Although employed primarily as a benchmark for visual short term memory representation, the results regarding the Size JND have significant theoretical implications as discussed above. The first specific area of interest is to consider more closely the Size JND, and more broadly the role of attention in the maintenance of high fidelity information.

The present thesis suggests that attention to the representation can reduce the rate of decay, but cannot stop it. One way of investigating this further is to more closely examine the time course of decay both under attentional interference and control conditions. The maintenance intervals chosen in the present studies were constrained by the protocol of the n-back tasks. It would be interesting to look more closely at shorter maintenance intervals and smaller increments in maintenance interval. This would allow for both examination of the time course of the decay and allow quantification of how much this can be slowed by allocation of attention. A further concern with the protocol employed in the JND regards the levels of size differences employed in the JND. In the present thesis the size difference decreases in intervals of 10%, as such the span level achieved is rather coarse. Performing the task with smaller changes in size would allow for a finer representation of the stimulus' fidelity in memory.

The results observed under interference by irrelevant speech suggest that across the increasing maintenance intervals, there may be a differential dependence of visual and verbal representation. It was shown that by 8.5seconds, the representation had decayed and stabilised this point was taken as representing the representation being held in categorical form. It is at this point that there was a hint of an effect of irrelevant speech. It would be interesting to observe this more closely across increasing maintenance intervals and with a larger and more varied sample of participants.

9.4.2. Visual Matrix Patterns

With regards to the matrix patterns, it would also be of interest to employ a wider range of maintenance intervals. The high semantic matrix patterns showed no decay across the three maintenance intervals employed. Andrade et al (2002) observed the same phenomenon at intervals up to 36seconds, and as such it would be interesting to observe high semantic matrix pattern performance over equivalent intervals.

The nature of the difference between the high and low semantic patterns was shown to be reliable and produced consistent results. However, in the present thesis, chunking of the patterns was not assessed directly, instead the superiority of the high semantic patterns over the low was taken as an index of effective effortful chunking. This was because the present study was exploratory in assessing the superiority of semantic representation and the relationship between chunking and executive resources. It is important for future research to perhaps aim to quantify these chunks and further specification of the matrix patterns is needed to identify variation is other forms of redundancy such as symmetry and other gestalt properties, and finer differences in the type of semantics employed (i.e. visual rather than verbal).

It was discussed above, that differences between target and distracter stimuli in the matrix pattern task could affect the need for high resolution representations (Awh et al, 2007). It is possible that as the high semantic patterns contained more familiar forms than the low, resulting in a decreased reliance on high resolution representation due to changes in the pattern resulting in more striking differences between 'same' and 'different' version of the pattern. Although this was controlled for to some extent in the development of the patterns by only ever moving one cell by one cell and avoiding changes in obvious chunks in the pattern. It would be beneficial to analyse, in a further study, subjective ratings of difference between study and target and distracter patterns and whether this differs between high and low semantic sets.

Overall, it must be noted that the two forms of matrices have demonstrated clear differences in behavioural data. And as such are very promising, with further analysis of the matrices suggested above, the patterns can be used to build on the results of the present thesis to characterise the nature of the integration of short and long-term representations in visual working memory.

9.6. Conclusions

The data from this thesis have interesting theoretical implications for the modelling of working memory. This was discussed in detail throughout the general discussion, but it appears that each model introduced in the literature review can accommodate the results to differing degrees and perhaps support modification or further specification of components of the models discussed.

One overriding conclusion arising from the data is that all of the tasks appear to automatically activate some categorical representation. This implicates models of activated LTM, although the multi-component models of working memory specify very strong links with LTM. The simplest explanation is that the contents of working memory are LTM representations activated above threshold. This account lends support for Cowan’s (2005) embedded processes model of working memory. This model accommodates the present data more simply and directly than the other models discussed with the exception of the JND data. The allocation of attention to the representation does not eliminate decay; it does however slow the decay. This doesn’t run contrary to the embedded processes model but it does mean some specification of the focus of attention is necessary and perhaps a greater description of the notion of sensory memory.

When discussing time limits to the focus of attention, Cowan (2005) suggests there is potentially no limit. The present thesis proposes a modification to this assumption by specifying a time limit to the focus of attention with regards to the resolution of a representation which does not afford semantic support. Although this will need further investigation, it is consistent with previous literature showing decay of representations in the absence of interference.

Baddeley’s Episodic Buffer model (2000) does not run contrary to the results of the present experiment, nor does it contradict Cowan’s model. Since the addition of the episodic buffer, there are striking similarities between the models, discussed in chapter 3. Each model takes a different approach. The Baddeley model attempts to precisely identify specific mechanisms such as visual and verbal processes and their functioning, whereas Cowan's model is more exhaustive in that it attempts to accommodate all types of representation by specifying common processes. The present results also have implications for Baddeley's (2000) model in that they appear to differentiate between automatic and effortful integration of LTM information into short-term representations. It appears that some 'chunking' occurs without the central executive, whereas further chunking of less salient semantic forms requires effortful processing and implicate the central executive. Baddeley et al (in press) have recently modified the function of the episodic buffer to be a passive store for chunks of information which may then be accessed by the focus of attention, thereby further increasing its similarity to Cowan's (2005) model. It appears that chunking may be much more automatic than previously thought. It is proposed that the notion of passive versus active formation and maintenance of bound information in working memory could prove to be a very interesting area of future research and that the present thesis has perhaps served to provide evidence for both active and automatic maintenance and binding of information.

APPENDICES

Appendix A

Number of RT responses per participant per condition for n-back task in Experiment 1.

	CONTROL	VPT	CORSI	JND
p001	10	7	6	7
p002	9	2	3	4
p003	4	0	4	3
p004	10	4	4	5
p005	11	1	4	6
p006	10	6	4	6
p007	11	4	4	4
p008	11	4	3	4
p009	8	1	4	5
p011	11	2	3	3
p012	9	5	6	5
p013	12	4	5	4
p014	12	3	6	5
p015	9	5	4	5
p016	8	2	5	6
p017	12	5	4	3
p018	6	2	4	5
p020	4	0	0	1
p021	12	2	2	0
p022	11	4	5	0
Mean	9.5	3.15	4	4.05

APPENDIX B

Standard Instructions on Semantic Classification Task

Instructions for participants

Please read the following instructions carefully, you will be presented with a series of black and white matrix patters of various sizes.

For each pattern you are required to rate how much of it you feel you can apply meaning to on a scale of 1 to 7 (1 = none; 7 = all). This is how much of the pattern you can remember by giving all or part of it labels or recognising shapes or configurations that you may be able to remember without being able to explicitly describe.

Please record your rating on the response sheet provided **before** selecting it on the keyboard.

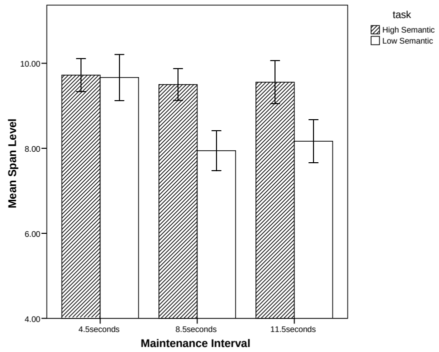
On the response sheet there is also space to provide a description of how you would remember each pattern, please provide as much detail as possible. There are no right or wrong answers.

Please now take a moment to ask the experimenter any questions you may have and press any key on the keyboard to begin.

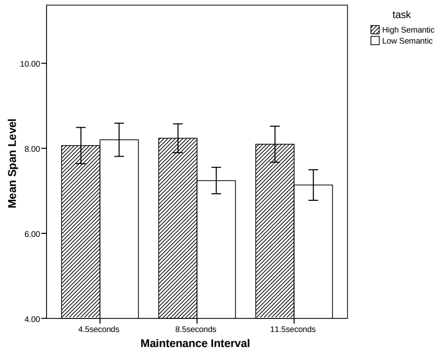
APPENDIX C

Graphs representing mean span performance for both forms of matrix task at each of the three maintenance intervals

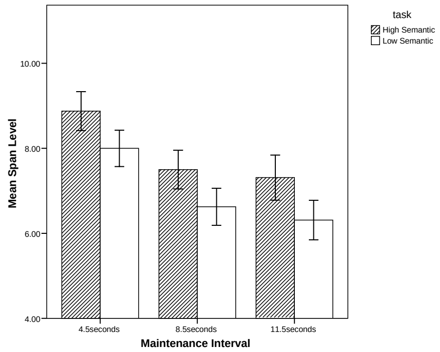
(a)



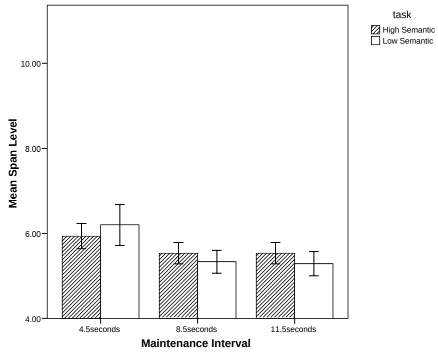
(b)



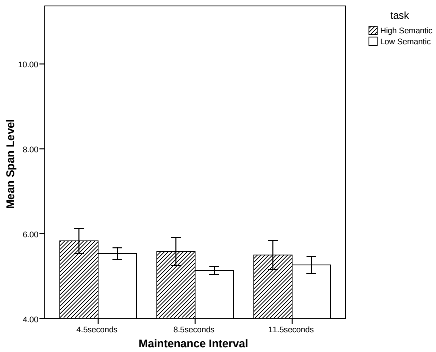
(c)



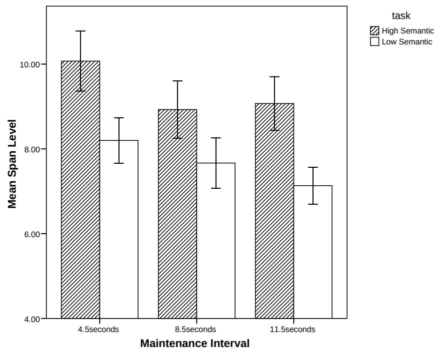
(d)



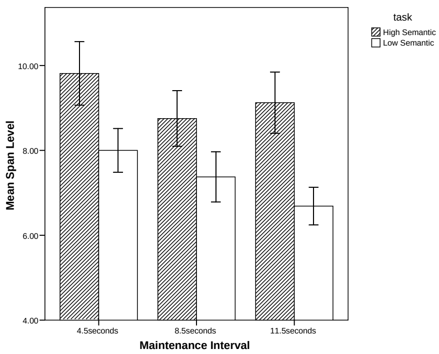
(e)



(f)



(g)

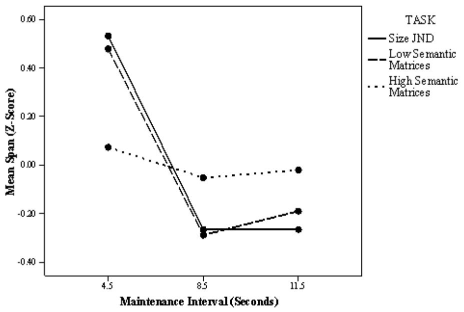


(a=control; b=replication; c=reduced encoding time; d=1-back; e=attentional interference; f=verbal interference; g=visual interference)

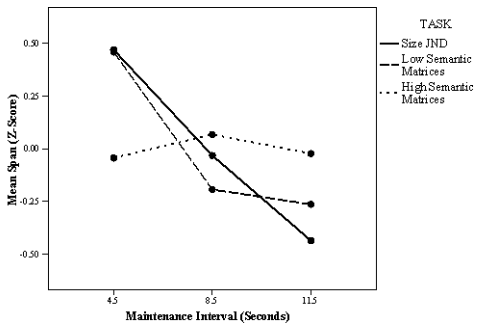
APPENDIX D

Line graphs from experiments 2, 3, 4, 5, 6 and 9 showing z scores of mean span performance for both forms of matrix pattern task and the Size JND across the three maintenance intervals employed

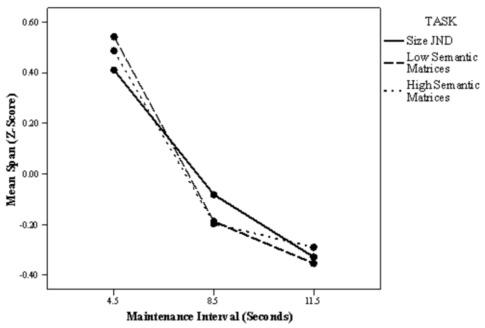
(a)



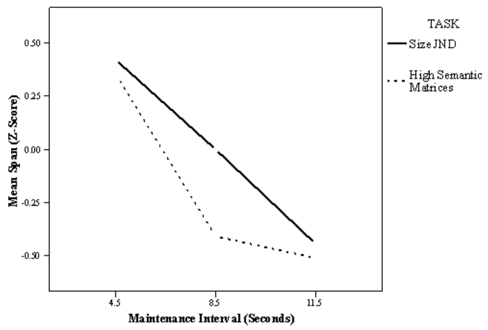
(b)



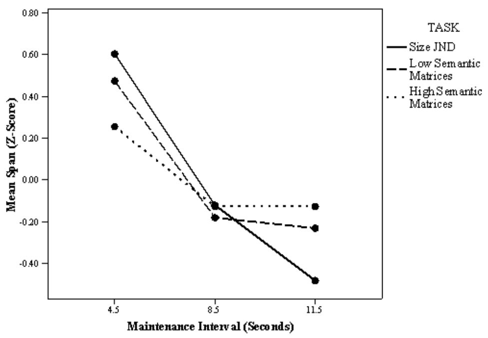
(c)



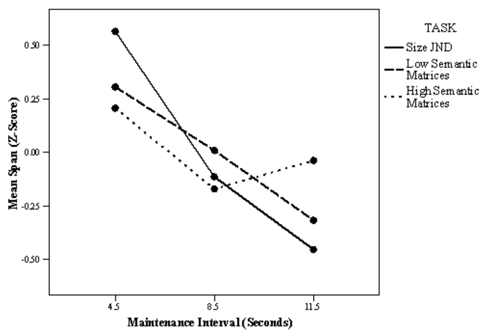
(d)



(e)



(f)



(a=control; b=replication; c=reduced encoding time; d=2-back; e=1-back; f=visual interference)

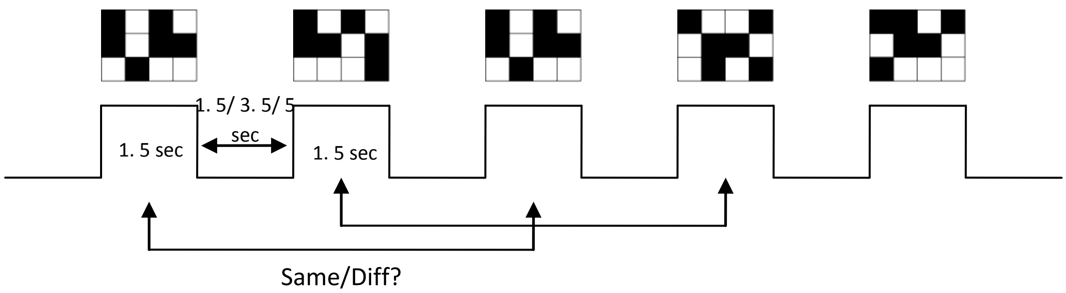
APPENDIX E

Participant information for the 2-back patterns task

Participant Information

This study aims to look at your memory for visual patterns over different lengths of time and your ability to update the information stored in your memory.

In this study you will be shown a series of black and white matrix patterns over different time intervals (either 1.5seconds, 3.5seconds or 5seconds between presentations). For each pattern you are presented with you will be asked to judge if it is the same or different as the pattern you were presented with 2 beforehand. The patterns will increase in size until it is the largest pattern you can reliably remember. You will be asked to complete this task for the 3 different time intervals.



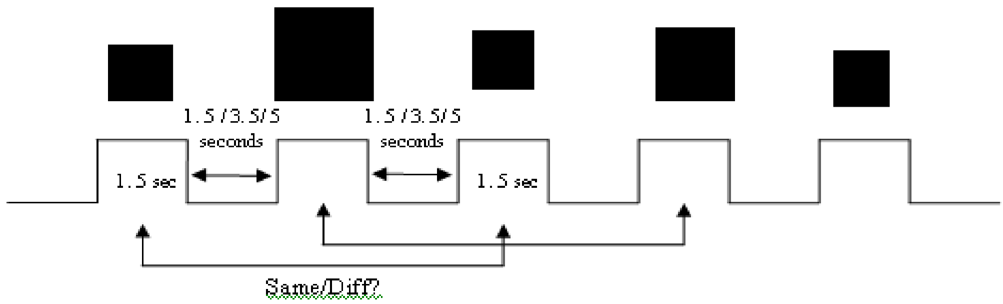
APPENDIX F

Participant information for the 2-back JND task

Participant Information

This study aims to look at your memory for size over different lengths of time and your ability to update the information stored in your memory.

In this study you will be shown a series of squares of varying sizes over different time intervals (either 1.5seconds, 3.5seconds or 5seconds between presentations). For each square you are presented with you will be asked to judge if it is the same or different size as the square you were presented with 2 beforehand. The size difference between the squares will decrease until it is the smallest size difference that you can reliably discriminate. You will be asked to complete this task for the 3 different time intervals.



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