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FEATURE BINDING IN VISUO-SPATIAL WORKING MEMORY

by

JANE VICTORIA ELSLEY

A thesis submitted to the University of Plymouth in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

School of Psychology Faculty of Science

March 2007

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JANE VICTORIA ELSLEY FEATURE BINDING IN VISUO-SPATIAL WORKING MEMORY

Abstract

Four series of experiments using a paradigm adapted from Prabhakaran et al. (2000) are presented exploring the characteristics of bound visuo-spatial representations in memory. This thesis was guided by the following theoretical guestions: (1) Can location binding be demonstrated in a recognition paradigm? (2) What are the temporal dynamics of location binding? (3) Is location binding automatic, or rather, does it require attentional resources? (4) What are the products of location binding: Whole new objects or links between features that contribute in an asymmetrical manner? Series 1 addressed the first question through the demonstration of binding effects across two experiments. Series 1 was additionally informative with respect to the second question in demonstrating that binding emerged relatively early (within 250ms post stimulus offset) and could be maintained for at least four seconds. With regard to the automaticity with which visual and spatial features are integrated, and the characteristics of the resulting bound representations, three lines of evidence are reported. Firstly, by manipulating feature relevance, Series 2 demonstrated that binding may occur automatically when shapes are attended, but not when locations are attended. This finding is not easily compatible with the idea that location binding results in the creation of an entirely new construct in memory which would predict binding effects when either shapes or locations are attended. Secondly, it was demonstrated that increasing the amount of attention necessary for encoding the shape features enhanced the binding which took place when shapes only were attended (Experiment 3B) but had minimal effect on performance when locations only were attended (Experiment 3C). This suggests that while binding to location may occur automatically when shapes are the attended feature, the amount of attention allocated to those shapes may increase the size of the binding effect which ensues. Thirdly, it was demonstrated that the binding effect following attendance to both features was significantly reduced, but not eradicated under attentional load conditions (Experiment 4) suggesting that while binding to location may in part emerge automatically, bound representations may benefit from available attentional resources. The results are discussed in terms of a hierarchical structure to encoding in memory (e.g., Jiang et al., 2000) which suggests that the encoding of the spatial layout of the scene must occur prior to the encoding of what occupies those locations (see also Navon, 1977). We speculate that location binding in memory may be characterised by links formed between features in memory, while the feature information is itself stored in parallel (e.g., Wheeler & Treisman, 2002). In addition, the links may be unequally weighted, an aspect of binding which may arise as a result of the order of encoding visual and spatial features.

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At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Committee. This study was financed with the aid of a studentship from the Economic and Social Research Council. Relevant scientific seminars and conferences were regularly attended at which work was presented; external institutions were visited for consultation purposes and several papers prepared for publication (not yet submitted).

Conferences Attended

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INTRODUCTION

1. Overview

Working memory (WM) plays an important role in everyday complex tasks. The concept refers to a cognitive system capable of maintaining information over short periods of time, and further, able to update and manipulate information in order to facilitate problem solving. Visuo-spatial working memory (VSWM) is limited to the processing of non-verbal information, and has been distinguished from verbal working memory in much experimental research (e.g., Della Sala & Logie, 1993; Logie, 1995; Logie, Zucco & Baddeley, 1990; Smith & Jonides, 1997).

The division of verbal and visuo-spatial processing has been incorporated into explanatory models of WM, for example in the Working Memory Model (Baddeley & Hitch, 1974; Baddeley & Logie, 1999) where emphasis is placed on the independence of storage modules. Consistent with this modular framework, evidence suggests that VSWM itself may be subdivided into separate factions responsible for the processing of visual and spatial information (see Logie, 1995). Supportive evidence for the division of visual and spatial memory has been demonstrated in varying fields of research, for example double dissociations between patients with brain trauma (e.g., Farah, Levene & Calvanio, 1988; Luzzatti, Vecchi, Agazzi, Cesa-Bianchi & Vergni, 1998); double dissociations shown by healthy participants in selective interference tasks (e.g., Della Sala, Gray, Baddeley, Allamano & Wilson, 1999); and in developmental research (e.g., Logie & Pearson, 1997). Brain imaging studies also support the existence of distinct pathways in the brain for processing visual and spatial information (e.g., Courtney, Ungerleider, Keil & Haxby, 1996; Ungerleider & Mishkin, 1982).

While there is a multitude of evidence suggesting independent processing of visual and spatial information, the visual world is not experienced as composed of fragmented object features. At some point these disparately processed features need to be recombined. This is the crux of the binding problem. Recent VSWM investigation has turned to explaining how and when visual and spatial features are integrated in memory, referred to as location binding. An illustrative example of location binding in VSWM is where one type of visual

feature, such as an object's shape must be correctly associated with its location to provide a unified representation of that object. More practically, the ability to correctly locate a particular item in a visual array of multiple items is a basic task carried many times per day. From reaching for a blue pen, to locating a red letterbox, binding to location serves a pertinent role in our day-to-day existence.

The location binding problem spans both perception and memory, as correctly perceiving an item in a location may inform the memory trace used to later recall where the item was last seen. The issue is further bolstered by evidence suggesting that visual and spatial information are initially processed in parallel by separate processing streams. Further, up until recently, influential models of WM (e.g., the Working Memory Model, Baddeley & Hitch, 1974) have emphasized the modularity of processing, affording a climate where experimentation has aimed to demonstrate the independence of visual and spatial processing modules, at the cost of understanding how such information may be maintained in concert (c.f., Baddeley, 2000). The result is that the location binding problem in VSWM remains poorly understood.

This thesis aimed to add to our understanding of how and when visual and spatial features are integrated in VSWM, with a view to answering the following key theoretical questions: (1) Can we demonstrate location binding in a recognition paradigm? (2) What are the temporal dynamics of location binding? (3) Is location binding automatic, or rather, does it require attentional resources mediated by task driven goals? And (4) what are the products of location binding? (whole new objects or links between features that contribute in an asymmetrical manner). The pertinence of answering each of these key issues will become more apparent as research in relation to binding and WM is discussed; and each question will be re-iterated with regard to current literature as the report progresses. Evidence in favour of a division between the processing of visual and spatial information will form the basis of the following section.

2. Working Memory: Differentiating the 'What' and the 'Where'

2.1 Behavioural Evidence and the Double Dissociation Paradigm

Within the context of visuo-spatial memory, behavioural evidence has investigated extensively the separability of the storage of visual and spatial information, and a large body of data suggests that the two classes of information are indeed processed independently. In the context of location binding, such evidence emphasises the issue of how visual and spatial classes of information are integrated in memory.

Cognitive behavioural experimentation has made use of the 'double dissociation' paradigm which capitalises on selective interference effects in order to tease apart processes contributing to memory for visual and spatial information classes. The existence of selective interference effects is well documented in the literature. For example, in the visual domain, irrelevant pictures (e.g., Logie, 1986; Zimmer & Speiser, 2002), dynamic visual noise (DVN: e.g., Quinn & McConnell, 1996b), and coloured flicker arrays (Hecker & Mapperson, 1997) have been shown to selectively interfere with visual memory (contrast with Andrade, Kemps, Wernier, May & Szmalec, 2002, who highlighted the difficulty in replicating the effect of DVN suggesting its disruptive effectiveness pertains only to visual imagery). In contrast, a multitude of spatial interference tasks have been successfully shown to disrupt spatial memory, for example, spatial tracking (e.g., Baddeley & Lieberman, 1980); spatial tapping (e.g., Smyth & Pendleton, 1989); arm movements: imagined and passive (e.g., Johnson, 1982; Quinn & Ralston, 1986, respectively), voluntary eye movements (e.g., Baddeley, 1986) and black and white flicker arrays (Hecker & Mapperson, 1997). General consensus has now been reached that many spatial interference effects are probably artefacts of shifts in spatial attention (e.g., Awh & Jonides, 2001; Smyth & Scholey, 1994).

Selective interference experiments operate on the premise that a visual primary task will be interfered with by visual, but not spatial secondary tasks, by virtue of shared common resources (or competition within memory stores: e.g., Baddeley & Hitch, 1974). The addition of a lack of interference elicited by a spatial secondary task on the visual primary task forms a single dissociation between visual and spatial memory processes. In order to form the more persuasive double dissociation, the reverse relationship must also hold; that is, a spatial primary task should suffer interference from a spatial secondary task, but not a visual-based

secondary task.

Task selection in this sort of paradigm is pivotal, such that primary tasks must tap only visual or spatial memory respectively (although in practice, visual and spatial processes in any given task often overlap). Established visual primary tasks include the Visual Patterns Task (VPT: Della Sala, Gray, Baddetey & Wilson, 1997); and a widely used spatial task is the Corsi Blocks Task (CBT: e.g., Milner, 1971). The former requires memory for static matrix patterns, while the latter, for a spatiotemporal sequence of locations. Both were used to great effect by Della Sala et al. (1999). In their selective interference experiment, they utilized irrelevant pictures (abstract paintings) as a visual interference task; and spatial tapping (requiring participants to tap pegs in a square array) as a spatial interference task, on the premise that independent processing predicted that irrelevant pictures would interfere with the VPT but not the CBT, while spatial tapping would interfere with performance on the CBT, but not the VPT. The experiment successfully demonstrated a double dissociation, lending further evidence to the notion that visual features and spatial features are stored independently. More recently, independent processing effects were demonstrated by Klauer and Zhao (2004) who observed robust double dissociation effects across a series of experiments, while carefully controlling for possible confounding variables (see also Hecker & Mapperson, 1997; Tresch, Sinnamon & Seamon, 1993).

Double dissociations have also been demonstrated by crossing performance in patients with selective impairments in visuo-spatial abilities. For example, Farah et al. (1988) reported on a patient (LH) who showed deficits in visual but not spatial memory. Conversely, Luzzatti et al. (1998) reported on a patient (EP) whose deficits manifested in the opposite way, namely, deficits in spatial, but not visual abilities. Similarly Della Sala et al. (1999) reported that two participants from their patient sample performed poorly on the CBT, but above average on the VPT, while another patient showed the opposite pattern of results. Double dissociations of this kind are not without problems (i.e., deficits may extend beyond visual or spatial abilities; compensatory mechanisms may have developed; and as noted by Pickering, 2001, patient deficits rarely manifest in the same way; see also Baddeley, 2003) but they are compelling when taken in concert with behavioural evidence in demonstrating the relative independence of the storage of visual and spatial information. In addition,

developmental research also indicates the separability of cognitive streams responsible for the encoding of visual and spatial information. Experimentation with children aged between 5 and 11 suggest that the developmental trajectories of visual and spatial memory diverge as age increases, such that a visual over spatial memory advantage found in younger groups enlarges as a function of increasing age. This suggests independent cognitive development of processes responsible for visual and spatial processing respectively (Logie & Pearson, 1997). Behavioural evidence from a broad variety of disciplines therefore compellingly argues for the independent processing of visual and spatial information classes.

However, there are some discrepancies between findings. For example, some authors have demonstrated behavioural overlap in the encoding of visual and spatial information (e.g., Downing, 2000; Jiang, Olson & Chun, 2000; Olson & Marshuetz, 2005), suggesting that one type of information cannot be maintained independently of the other. Discussion of these issues will form the basis of Section 4.3. However, neuropsychological investigation has further extended the dissociation findings, indicating that visual and spatial processing streams can be mapped on to separable areas within the brain; this will be discussed in the following section.

2.2 Neuropsychological Evidence: 'What' and 'Where' Pathways

Neuropsychology is a further field of research where extensive investigation has aimed to demonstrate the independence of visual and spatial processing in the cognitive system. The findings compliment the behavioural data in suggesting that visual and spatial information can be processed independently within the brain. More specifically, results carried out with both human (e.g., Darling, Della Sala, Logie & Cantagallo, 2006; Ungerleider & Haxby, 1994) and non-human participants (e.g., Ungerleider & Mishkin, 1982) converge in suggesting that visual and spatial information are initially processed in functionally specialised, distinct pathways. The occipitotemporal (or ventral) pathway is thought to be decisive for the identification of visual objects and contains cells that specialise in the processing of object features such as colour, shape, texture and orientation (Desimone & Ungerleider, 1989). The occipitoparietal (or dorsal) pathway on the other hand has been identified as responsible for the processing of spatial information (Ungerleider & Mishkin,

1982).

Neuropsychological investigation in humans has supported this specialisation in investigation of clinical patients with area specific brain lesions and in brain imaging studies. On the former, Newcombe, Ratcliff and Damasio (1987), using face recognition as a visual task and maze learning as a spatial task, found that occipitotemporal lesions resulted in deficits on the visual but not the spatial task, whereas occipitoparietal lesions resulted in deficits on the spatial, but not the visual task.

In brain imaging studies, many techniques have been used in investigation of the ventral versus dorsal distinction, e.g. positron emission tomography (e.g., Courtney et al., 1996; Smith, Jonides, Koeppe, Awh, Schumacher, & Minoshuma, 1995); visual evoked potentials (VEP e.g., Brigell, Strafella, Parmeggiani, DeMarco & Celesia, 1996), a large number of which have found support for the distinction. For example, Courtney et al. (1996) utilized positron emission tomography techniques to measure changes in regional cerebral blood flow resulting from the processing of the two classes of information. Results indicated (with face identification as their visual task, and spatial location identification as their spatial task) that the visual task preferentially activated ventral regions (specifically, in fusiform, parahippocampal, inferior frontal, and anterior cingulated cortices, and in the right thalamus and midline cerebellum), whereas the spatial task activated dorsal regions (specifically, the inferior parietal cortex, and in the superior frontal sulcus). Both stimulus classes activated the frontal cortex (see also Raffone & Wolters, 2001).

The dorsal versus ventral distinction has further guided methodology used to demonstrate behavioural double dissociations. For example, Hecker and Mapperson (1997) sought to gain evidence for a double dissociation between processes mediated by the magnocellular subsystem (closely related to the dorsal stream) and parvocellular subsystem (closely related to the ventral stream). Using shape selection as a primary visual task, and location selection as their primary spatial task, they imposed two interference conditions. The visual interference condition entailed a colour flicker, and the spatial interference condition entailed a black to white flicker, guided by evidence suggesting that the former would interfere with the parvocellular stream, and not the magnocellular stream, whereas the latter with the magnocellular stream but not the parvocellular stream (see also Brigell et al., 1996). Results

indicated that the colour flicker had a detrimental effect on performance in their visual task, but not their spatial task, whereas the black and white flicker produced interference on their spatial task, but not their visual task.

Research discussed so far demonstrates compelling evidence for the separability of processes mediating visual and spatial memory, not least, because the two information classes appear to be processed in spatially distinct brain regions. True for both behavioural and neuropsychological demonstrations however is that both have been motivated to demonstrate the relative independence of visual and spatial information storage. While there is a large body of evidence suggesting that visual and spatial information are encoded independently, a number of neuropsychological studies have failed to note separable effects for the two classes of information (e.g., D'Esposito, Ballard, Zarahn & Aguirre, 2000; Nystrom, Braver, Sabb, Delgado, Noll & Cohen, 2000) indicating, similarly to the behavioural studies, that there may be a degree of cross-talk between the visual and spatial streams. However, neuropsychological evidence further suggests functional specialisation for bound representations, and corresponding neural correlates (e.g., Prabhakaran, Narayanan, Zhao & Gabrieli, 2000; Simon-Thomas, Brodsky, Willing, Sinha & Knight, 2003). These issues will discuss in more depth in Section 5.

With such a wealth of evidence suggesting that visual and spatial information are processed independently, the location binding problem becomes even more apparent. How are these disparately processed information classes bound in memory so that we are able to retain where visual objects are located? Does the cross-talk between streams observed in neuropsychological studies represent some binding of visual and spatial features? Before evidence for the integration of visuo-spatial memory is discussed, the Working Memory Model (Baddeley & Hitch, 1974) will be described, due to the fact that its independent processing architecture has motivated much of the cited empirical investigation.

3. Independent Processing and the Working Memory Model

Working memory is a cognitive system enabling the maintenance and manipulation of information over short periods of time. According to Baddeley and Hitch (1974), in a development of earlier concepts assuming unitary storage (e.g., Atkinson & Shiffrin, 1968). working memory assumes a 'tripartite' structure, with emphasis on independent processing of different classes of information. More specifically, the Working Memory Model in its present state encapsulates four interacting subsystems, affording information processing above and beyond the simple capacity for storage. The model in its original form (Baddeley & Hitch, 1974) assumed three distinct components (see Figure 1): a central executive; and two slave systems: a phonological loop; and a visuo-spatial sketchpad (VSSP). Recently, Baddeley (2000) proposed a fourth component, the episodic buffer, which was added to the model in an attempt to boost explanatory power of how distinct classes of information can be integrated. As we will see, this has become a key theoretical point of investigation in the literature, and the model in its original form fell short of being able to fully account for binding data. Discussion will begin with the Working Memory Model in its original form (Baddeley & Hitch, 1974), while the episodic buffer component will be introduced in Section 5, following an indepth review of the binding literature.



Figure 1. The Working Memory Model (Baddeley & Hitch, 1974).

The structure of the WM model is such that two slave systems (the phonological loop and the visuo-spatial sketchpad) assume responsibility for storage and manipulation of verbal and non-verbal information respectively, controlled and coordinated by a central executive (CE). The CE (based on Norman & Shallice's, 1986, supervisory attentional subsystem) assumes attentional control and regulation of the working memory system through the coordination of the phonological loop and the VSSP (e.g., Baddeley, Bressi, Della Sala, Logie & Spinnler, 1991). Central executive processes have further been implicated in selective attention (e.g., Baddeley, Emslie, Kolodny & Duncan, 1998); attention switching; in divided attention (e.g., Baddeley, Baddeley, Bucks & Wilcock, 2001) and in activating representations within long-term memory. The CE is not itself assumed to have any function pertaining to information storage. A recent role attributed to the CE is the attentional binding of disparately processed information from the two slave systems, and from long-term memory within the episodic buffer component of the working memory model. Central executive function with regard to binding will be discussed in the context of the episodic buffer in Section 5.

The phonological loop is assumed to be responsible for the processing of verbal information, and comprises two distinct modules: a capacity limited phonological store, which represents material in a phonological code; and an active rehearsal system which serves to refresh material in the phonological store through sub-vocalisation (c.f. Macken & Jones, 2003, who question the need for a short-term phonological store). The capacity of the phonological loop is limited by the number of words that can be articulated in two seconds. This is reflected in the word length effect for example, whereby verbal recall is restricted by the length of the words being retained (e.g., Baddeley, Thomson & Buchanan, 1975), so that a list of shorter words is typically easier to recall than a list of longer words. Without rehearsal within this system, information in the phonological store decays rapidly (Baddeley & Hitch, 1974). The phonological loop has further been implicated in counting (e.g., Logie & Baddeley, 1987); in language comprehension (e.g., Vallar & Baddeley, 1984); and in mental arithmetic (e.g., Logie, Gilhooly & Wynn, 1994).

Evidence in favour of a purely phonological store has been evidenced through the phonological similarity effect, where memory accuracy for a series of letters or digits is adversely affected by the degree to which those items sound similar (e.g., Baddeley, 1966). Further, the model predicts that verbal material is treated differently as a function of whether it is presented visually or auditorily. Auditory stimuli are assumed to gain direct access to the phonological store (e.g., Baddeley, Lewis & Vallar, 1984). However, visually presented information can gain access through the process of sub-vocalisation within the active rehearsal mechanism. Evidence in favour of this has been found in tasks using articulatory

suppression (e.g., Baddeley et al., 1975). An articulatory suppression task typically involves the repetition of an irrelevant word or series of words while concurrently carrying out some other primary task, a process assumed to be undertaken by the active rehearsal system. Evidence suggests that when verbal items are presented visually, articulatory suppression removes the phonological similarity effect presumably because the active rehearsal system could not be employed to sub-vocalise the information. However, when verbal information is presented auditorily, direct access to the store is reflected in the resilience of the phonological similarity effect to articulatory suppression. Finally, while considered separate entities, the phonological loop is assumed to rely heavily on long-term memory. For example, memory capacity for familiar words is superior to that of unfamiliar words (or nonsense syllables) indicating some top-down feed from long-term stored knowledge (e.g., Baddeley, Vallar & Wilson, 1987).

In contrast, the visuo-spatial sketchpad is assumed to be responsible for the retention and manipulation of visual and spatial information, and is seen as independent from the phonological loop as a result of much experimental research (e.g., Baddeley, 1986; Della Sala & Logie, 1993; Logie, 1995; Logie, Zucco & Baddeley, 1990; Smith & Jonides, 1997). However, relative to the phonological loop, less is known about its functional characteristics.

Research over the last decade indicates that similar to the phonological loop, the sketchpad may be fractionated into two subcomponents, one responsible for the control of visual information, and the other for control of spatial information. Within the context of the working memory model, Logie (1995) postulated that the VSSP is subdivided into a 'visual cache' and an 'inner scribe'. The visual cache is argued to be responsible for the temporary storage of information about object form and colour, and as such is visual in nature, while the inner scribe is responsible for rehearsal and storage of information about movement sequences, and is spatial in nature.

We have already seen in the previous section that there is much empirical support for the visual and spatial distinction. To re-cap, evidence for the separability of these subcomponents comes from double dissociations between patients following brain trauma (e.g., Farah et al., 1988; Luzzatti et al., 1998); double dissociations in healthy participants in selective interference tasks (e.g., Della Sala et al., 1999); and developmental research (e.g.,

Logie & Pearson, 1997), and most have been interpreted and indeed motivated by the Working Memory Model architecture. It should be noted that there has been variation in terminology with regard to the division of the VSSP, with some authors opting for a 'passive' versus 'active' distinction (e.g., Logie, 1995; Vecchi & Cornoldi, 1999), while others adopt a 'static' versus 'dynamic' distinction (e.g., Pickering, 2001). The present report uses the terms *visual* and *spatial*, respectively.

Relative to the phonological loop little is known about the process of rehearsal within the VSSP, although Baddeley (2001) proposed that attention may be the medium of rehearsal, operating through the central executive. In terms of capacity, experimental research demonstrates that typically around 4 items can be maintained (e.g., Cowan, 2001), but limitations vary as a function of the stimuli presented. For example, VSTM can retain around 4 simple visual features (e.g., Luck & Vogel, 1997), and approximately 6 spatial locations (e.g., Simons, 1996). Analogous to the phonological similarity effect however, evidence suggests that the capacity of the VSSP may be further limited by the degree to which visual items are similar (Hitch, Halliday, Schaafstal & Schraagen, 1988).

The working memory model therefore is well equipped to account for evidence suggesting that visual and spatial information is processed independently. One controversy surrounding the VSSP, and the working memory model in general, is the fact that evidence suggests that visual features and spatial features - assumed to be processed within the respective components of WM - can be 'chunked' in order to increase capacity. The lack of explanatory power of the model for binding evidence (along with other evidence in the verbal domain) spurred the proposal of the episodic buffer, which will be discussed in Section 5. The following sections focus on empirical evidence for visuo-spatial binding, and highlight the need for further explanation within the working memory model. The next section discusses binding in relation to VSWM capacity.

4. Working Memory: Integrating the 'What' and the 'Where'

4.1. Capacity Limits and Binding Economy

The capacity of WM is constrained to around 4 items (e.g., Cowan, 2001), with estimations varying on the basis of the stimuli presented. As we have seen, VSWM can retain around 4 simple visual features (e.g., Luck & Vogel, 1997), but approximately 6 spatial locations (e.g., Simons, 1996). The availability of an unambiguous definition of the term *item* is important for clear understanding of the true capacity limitations of VSWM. It is more or less established in verbal WM that capacity limitations pertain to integrated chunks of information (Miller, 1956), but less is known about how item features can be bound in VSWM, and the storage economy or processing facilitation made possible through binding. More generally than the question of how objects are bound to their current locations in memory, recent experimentation has been directed at the simple question of whether VSWM can store chunked visuo-spatial features, or whether features are maintained independently, in parallel with no need for binding. Evidence for binding within WM suggests that visual features can be bound to specific circumstances.

One method to assess binding in VSWM is to consider the economy made possible through binding features together in terms of memory capacity. For example, if VSWM capacity is constrained by fully integrated representations, performance should not be affected by increasing the number of features (e.g., colour, shape, orientation) comprising items in a to-be-remembered (TBR) array but, rather, by increasing the number of items present in the array. Conversely, if WM capacity is limited by features, performance would be constrained by the number of features comprising each item.

Evidence for the full integration of features using this type of paradigm was demonstrated by Luck and Vogel (1997; also see Vogel, Woodman & Luck, 2001), although some of their findings are consistent with an alternative explanation (e.g., Wheeler & Treisman, 2002), as discussed below. In one experiment, using a change detection task, a TBR array was presented consisting of 2, 4 or 6 coloured, oriented bars. Participants had the task of remembering the colour, the orientation, or both the colour and orientation of the bars. Results indicated that for a given set size, performance in the conjunction condition (requiring

double the memory load compared to the feature conditions) was not significantly different to that in the feature conditions. The implication was that participants were able to retain two features of a stimulus as accurately as they could retain just one feature, supporting the visual-spatial 'chunking' hypothesis. In a further experiment, Luck and Vogel (1997) extended the findings to objects each composed of four features, whereby memory capacity quadrupled on the feature level, limited only by the number of objects in the array.

The alternate account for binding, consistent with Luck and Vogel's findings for features from different dimensions (i.e., colour and orientation) proposes that the doubling in memory capacity noted in binding studies is not due to binding per se, but rather due to the fact that storage of features from different dimensions is carried out in parallel, mediated by distinct capacity limited resource pools (e.g., Wheeler & Treisman, 2002). One key finding of Luck and Vogel's (1997) study was an object benefit pertaining to features from the same dimension, namely colour-colour conjunctions. Their results suggested that memory capacity in the conjunction condition was identical to that in the single feature conditions, thus demonstrating an object-based encoding benefit for features from the same dimension, and a compelling argument against the parallel stores account.

Subsequent evidence however has disagreed with the notion that WM can store 'chunked' visual features. Firstly, evidence suggests that bindings between features are dependent on the availability of attentional resources (e.g., Wolfe, 1999; Wheeler & Treisman, 2002; see Section 5). More specifically, subsequent research has failed to replicate Luck and Vogel's (1997) pivotal colour-colour binding results (e.g., Delvenne & Bruyer, 2004; Olson & Jiang, 2002; Wheeler & Treisman, 2002; Xu & Potter, 1999). The reason for the discrepancy between the findings of Luck and Vogel (1997) and subsequent attempts to replicate remains unclear. However, Xu (2002b) noted an absence of binding for features varying only on the orientation dimension, and only on the colour dimension, suggesting that features from the same dimension cannot adequately be integrated in VSWM.

In order to reconcile these findings, Wheeler and Treisman (2002) proposed that parallel storage may be the best characterisation of binding in memory. Their model holds that features from different dimensions are stored in parallel, and draw upon their own capacity resources, apparently doubling the capacity of WM without implicit need for binding.

Binding between features from the same dimension therefore could not be well maintained, presumably because they draw upon the same resource pools and are subject to interference. Wheeler and Treisman (2002) noted that the parallel storage interpretation could account for Luck and Vogel's (1997) findings, without assuming the binding of features. Using a more direct test for binding, Wheeler and Treisman (2002) further found evidence that binding between features from different dimensions could be maintained, subject to attentional resources, and that this binding may be characterised by links formed between independently stored features. However, if attentional resources are directed away from binding, the features can fall apart (as demonstrated by a lack of binding noted when a 'whole-display' probe was used, versus when a 'single probe' was used, Experiment 4B).

Consistent with the idea that VSWM can support binding between features under some circumstances are the findings of Olson and Jiang (2002). They directly assessed object-based versus feature-based capacity limitations in WM. They tested three competing hypotheses pertaining to the nature of representation in VSWM. Their *strong-object* hypothesis stated that VSTM is limited only by the number of objects, and not by the number of features comprising objects (e.g., Luck & Vogel, 1997). Their *strong-feature* hypothesis stated that the number of features comprising objects limits capacity, and that feature integration cannot extend this limitation (under which one would observe 'apparent' capacity benefits, while features are stored independently). Finally, their *weak-object* hypothesis stated that memory performance should be facilitated in conditions conducive to binding. For example, the efficiency with which bound representations are maintained may depend on how features are perceived, but that this benefit would not be as great as predicted by the strongobject hypothesis (i.e., doubled capacity).

Using a change detection task, their first two experiments failed to replicate Luck and Vogel's (1997) colour-colour integration findings, eliminating their strong-object hypothesis. Their third experiment tested memory for conjunctions comprising orientation and size features, and indicated that binding provided a capacity benefit similar to that for single features, rejecting their strong-feature hypothesis. In their final experiment, the strong-object hypothesis was assessed for multi-dimension features in order to ascertain whether features from different dimensions are bound in an obligatory fashion, or whether the maintenance of

features from different dimensions was better characterised by the parallel storage account. Results indicated that it was more difficult to store two integrated features relative to one feature, rejecting the strong-object hypothesis for multi dimension features. Finally, the parallel (independent) storage account was rejected on the grounds that memory performance was superior when features were conjoined to form objects relative to when they were spatially separated, suggesting that conjoining features somehow improved performance.

The authors asserted the weak-object hypothesis as the best characterisation of binding in memory, whereby capacity limitations pertain to both number of simple features, and number of objects, providing that in the latter, features are perceived as part of the same object (see also Woodman, Vecera & Luck, 2003).

Thus, WM capacity can be extended through binding, provided that features to be integrated are from different dimensions, and are perceived as belonging to one object. One may reject these findings on the grounds that spatially separated features used in Olson and Jiang's (2002) final experiment occupied more spatial locations than conjunction objects (i.e., twice as many spatial locations). Indeed, increasing the number of spatial locations occupied may constrain the direction of spatial attention, accounting for superior performance in the conjunction condition, where the number of spatial locations was less by virtue of features sharing spatial location. However, according to Lee and Chun (2001), the number of spatial locations that VSTM can indeed maintain features in a bound manner.

In sum, evidence suggests that the binding of visuo-spatial features can occur, and that increased capacity for bound features is not simply an artefact of features being processed in parallel. Additionally, the findings suggest that bound units are not by necessity stored in WM, as WM grants a role for individual features too. Therefore while features can be addressed independently, they can be bound together providing processing facilitation within the system. One of the key points to be addressed in the present thesis is whether the integration of features in memory results in the formation of a whole new 'object', or whether binding is better characterised by links between features, with the features in turn being stored independently (Wheeler & Treisman, 2002). Delineating these proposals as to the

mode of storage of bound representations is pivotal in establishing theoretical explanations for binding, and is particularly relevant given the proposal of the episodic buffer component of working memory (Baddeley, 2001) which prescribes that bound representations are stored in a separate memory buffer.

The experiments of Olson and Jiang (2002) further suggest that binding may be mediated by the way in which the perceptual system perceives visual features. Indeed, evidence suggests that items perceived as belonging to the same object are more likely to be encoded as such (e.g., Ceraso, Kourtzi & Ray, 1998; Delvenne & Bruyer, 2004; Walker & Cuthbert, 1998), whereas features perceived as belonging to different parts of objects are less well encoded (e.g., Xu, 2002a; 2002b). The characteristics of perceptual 'object-hood', and its relationship to binding in memory will form the basis of the subsequent section of this report.

4.2 Binding and Perceptual Object-hood

The importance of perceptual organization for feature binding in WM has been demonstrated in a string of recent experimentation. Specifically, evidence indicates a performance advantage of 'property binding' over 'part binding'. Property binding refers to features to be integrated forming properties of an object, for example, the colour of an orientated line. Conversely, part-binding refers to the integration of features located on different parts of an object, for example, a triangle on top of a square to form the percept of a house. Evidence indicates that the property binding advantage is most pronounced when processing relies on purely visual representation – the so called 'unitisation effect' (e.g., Asch, Ceraso & Heimer, 1960; Ceraso et al., 1998; Delvenne & Bruyer, 2004).

Asch et al. (1960) proposed that unitisation occurs as a result of direct links formed between features perceived as belonging to the same object, which result in spreading activation between a cued feature and linked features. Thus, retrieval of one feature results in the retrieval of all linked features (see also Wilton, 1989 for a similar proposition). Ceraso et al. (1998) investigated the unitisation effect, which predicts that features are more likely to be integrated if they are perceived as properties of the same object.

Ceraso et al.'s (1998) first experiment investigated whether processing differences

exist in the integration of *unitary* versus *separate* displays. Their unitary displays consisted of an outlined shape, made up of smaller coloured crosses. Separate displays consisted of an outline shape in black, some black cross forms, and a colour patch presented separately. Participants had the task of recalling multiple features from each display type. Results indicated that from the first encounter with unitary displays, properties were more likely to be recalled together. Conversely, for separate displays, properties were recalled in a fragmented manner (e.g., one at a time) on early presentations, but recall was enhanced with repeated exposure. The result was not an artefact of spatial proximity as their second experiment ruled this out as a mediating factor (see Lee & Chun, 2001).

Their third experiment assessed whether unitisation effects only occur for units, or whether they can also be induced for separate displays if features are grouped (based on Gestalt principles). Grouping was induced by manipulating 'common fate' for unitary and separate displays. Displays were either presented at a fixed location, or moved together in the same direction. They hypothesised that if grouping resulted in participants perceiving separate displays as a perceptual group, the grouping effect should be most pronounced on separate displays (as properties of unitary displays were already joined into a coherent group, and common fate would not add anything to this grouping). Results indicated that grouping did not induce higher levels of coherence for separate displays, suggesting that perceived unitariness has a special status in integration above and beyond the perceptual grouping of features. The authors proposed that the highest levels of integration occur when properties are simultaneously available for integration, and that spatial location is not the only factor contributing to binding.

Thus, perceived unitisation appears to support the integration of visuo-spatial features in memory. Evidence further suggests that this processing facilitation is limited to purely visual representation (Walker & Cuthbert, 1998). For example, the unitisation benefit is removed when features comprising unitary and separate displays are supported by verbal labelling. Walker and Cuthbert (1998) compared unitary and non-unitary displays with and without verbal recoding to assess the visual nature of the unitisation effect. In their Experiment 1 they assessed the unitisation effect with shapes varying in the degree to which they were nameable. Stimuli consisted of letters, geometric shapes, and nonsense shapes.

Unitary displays consisted of one of these forms appearing in a colour against a white background. Non-unitary displays consisted of a white form appearing against a coloured background. The task for participants was to state which colour went with which shape at recall. Their results indicated that there was no unitisation benefit for letter stimuli, but a significant unitisation effect for hard to name geometric shapes (assessed post-test) and nonsense shapes. Their second experiment tested the verbal contribution hypothesis using memory for hard and easy to name geometric shapes, while contrasting conditions where participants engaged in articulatory suppression (thought to suppress sub-vocalisation, and therefore preclude the attribution of verbal labelling: Baddeley & Hitch, 1974, see Section 3), and silent conditions. Results indicated that under articulatory suppression, unitisation effects emerged for both easy to name and hard to name shapes. Their Experiment 4 extended these findings to letter stimuli – when verbal labelling was precluded, a unitisation effect occurred even for these readily nameable stimuli.

The authors concluded that verbal memory is able to support associations across objects, whereas visual memory supports feature associations primarily while features are perceived to belong to the same object. In short, the unitisation advantage is limited to purely visual representations in the absence of verbal recoding. In terms of Asch et al.'s (1960) formulation, the authors asserted that unitisation reflects a more direct linkage in memory between features belonging to the same object than between features belonging to separate objects.

Similar effects supporting the integral role of object perception, or perceived unitariness in visual memory was demonstrated by Delvenne and Bruyer (2004). In their Experiment 2, using a change detection task, they presented participants with arrays consisting of shapes and visual textures as visual stimuli. They used two control conditions and two experimental conditions. In the shape condition, only shape stimuli were presented. In the texture condition, only textured patterns (filling black frames) were presented. In the unit condition, the shape stimuli were filled with the texture, so that the features were properties of the same object. In the non-unit condition, shapes (filled in black) were located inside a texture square in such a way that the shape and texture could be perceived to overlap. Participants had to indicate whether a second array was the same as, or different

from the TBR items. In the two *feature* conditions, a feature in the second array was new in half of the trials. In the unit and non-unit conditions, on half of the trials the features remained consistent, but the relationship between them changed, constraining memory for associations between features. Their results indicated that performance was superior in the unit condition compared with the non-unit condition (although at a slight time cost), suggesting that perceptual input is important for integration in working memory. Furthermore, performance in the unit condition was comparable to that in the single feature conditions, suggesting that unitised objects were retained just as single features in memory.

The authors reconciled their findings under the parallel storage account proposed by Wheeler and Treisman (2002) such that binding is possible for features from different dimensions; however, it is dependent on limited attentional resources. The retrieval of bound representations incurred a time cost relative to single features. Importantly, visual coherence (or unitariness) was a necessary perceptual condition for binding.

With evidence indicating that perceptual organisation, and specifically unitisation can support binding in working memory, Xu (2002a) asked the question of whether integration could occur across different *parts* of an object (part binding). Two experimental conditions (Experiment 3) were compared. Her stimuli consisted of objects that could be perceived as a beach ball with a stripe across the centre. In one condition, both colour and orientation features were carried by the beach ball stripe. In another condition, the colour attribute was carried by the ball, and the orientation feature was carried by the stripe. Disjunction displays (where circles, and oriented lines were presented spatially separated, as different objects), and single feature displays were presented as control conditions. The results indicated that two features were best encoded when they were from the same part of an object (i.e., the beach ball stripe), less well when they were from different parts of an object, and least well when they were spatially separated. Subsequent experiments replicated this finding with maths symbols, and 'mushroom-like' stimuli, demonstrating the robustness of the part binding versus property binding distinction.

In sum, the literature suggests that integration of visual stimuli in memory is mediated by the way in which perceptual mechanisms parse the visual display into units. Features constituting properties of an item are most readily integrated (the so-called unitisation effect:

e.g., Asch et al., 1960; Ceraso et al., 1998; Delvenne & Bruyer, 2004; Walker & Cuthbert, 1998). Furthermore, properties perceived as different parts of an object are more readily integrated than properties perceived as belonging to distinct objects (e.g., Xu, 2002a), but less well integrated than when they occur on the same part of an object. We now turn to the issue of location binding in WM.

As the integration of visual and spatial attributes inherently constitutes 'property binding' (a visual feature is always in a spatial location, thus spatial location is always a property of any visual feature), one may expect unitisation effects as envisaged by Asch et al. (1960) to apply to location binding. That is, once visual and spatial features are encountered, they are integrated by virtue of their perceived unitariness. Consequently, direct links could be created between features, and retrieval of one feature may result in the retrieval of all features. However, this does not seem to be the case for products of location binding in WM, where links between features seem better characterised as asymmetric. Location binding effects in memory will be discussed in the following section.

4.3 Location Binding in WM: Full Integration or Asymmetric Links between Features?

Fundamental to the issue of how visuo-spatial features are bound in VSWM is the question of how complete the resulting memory representation is following binding processes. As discussed above, binding in memory may take place via the memory system binding features together into a new structure or object; or, items may be stored independently, but bound via connections between features, which assert which features belong together, (e.g., Wheeler & Treisman, 2002). We have already seen compelling evidence for the integration of visuo-spatial feature dimensions ruling out the notion that features are simply stored independently with no bindings. Which is the best characterisation of binding in VSWM? According to the unitisation effect discussed above, the strength of links between features depends on how well those features are perceived as belonging to an object. Further guidance may be found in the perceptual binding literature, where according to 'object-file' theories of perceptual integration (to be discussed in more depth in Section 4.4), once an object is encountered, all of its features are entered into an object-file, implying the complete integration of features into one, high-order representation (e.g., Kahneman, Treisman &

Gibbs, 1992) addressed by spatial location (although without necessarily implying that features are linked, rather that they are grouped together in a common 'file'). In both cases, the encoding of feature A would be accompanied by the encoding (and integration) of feature B, and vice versa.

We have seen in previous sections that VSWM can support binding between visual features where features to be integrated form properties or parts of a perceived object. However, little is known about how visual features are bound to their current locations. Indirect evidence from location binding experiments suggests that full integration may not be the mode of storage in VSWM for products of location binding. For example, evidence suggests that the encoding of item identity is automatically accompanied by the encoding of spatial location while the reverse relationship does not hold (e.g., Jiang et al., 2000). This suggests that the integration of visual and spatial features (i.e., object identity, and object location) may result in *asymmetric* links between features.

In line with the asymmetry hypothesis, using a change-detection task, Jiang et al. (2000) demonstrated that spatial WM is based on configurations. Moreover, they found evidence that VSWM for stimuli location was not influenced by irrelevant changes in the colour or shape of items, but that memory for these visual features was disrupted when there was a mismatch between the locations of items between the TBR array and the probe. The authors proposed that VSWM may be organised in a hierarchical manner, such that when a visual image is encountered, a spatial configuration of items is automatically formed, and the features comprising the configuration are bound to the respective parts of the configuration. In short, the encoding of their visual stimuli did not take place without some memory reference to spatial location, while their location stimuli could be maintained in isolation of the visual features occupying them.

The term *configuration* within this context refers to the encoding of spatially distributed items in relation to one another (relative spatial location), rather than encoding each item's spatial location in isolation (absolute spatial location) which constitute two different classes of spatial representation. More specifically, a change in absolute location is defined as any change in location between the TBR array and the probe. Relative location change is defined as a change in location which alters the position of the target item relative

to some frame of reference (Olson & Marshuetz, 2005).

In a later study, Olson and Marshuetz (2005) directly assessed the question of whether the encoding of object identity results in the automatic encoding of spatial location. They were further interested to ascertain what type of spatial representation becomes encoded automatically when object identity is encoded, guided by the findings of Jiang et al. (2000) suggesting a role for relative spatial location. Using a change detection task, with a single face as a visual stimulus, participants had the task of indicating whether a probe face was the same as, or different from the TBR item, while changes in location were irrelevant. They compared three location change conditions. In their local change condition, the TBR item changed position relative to the surrounding reference frame, constituting a change in both relative and absolute location. In their global change condition, the memory item and the reference frame changed location so that the relative location of the TBR item to the frame was retained, but the absolute location of that item changed. These two conditions were compared to a no change condition, in which the face retained its initial position. The authors reasoned that if absolute location is automatically encoded, response times should be slower in the local and global change conditions relative to the no change condition. Conversely, if relative location is encoded, response times should be slower in the local change condition relative to the global change condition.

Their results indicated that responses in the local change condition were significantly slower than in the global change and no change conditions, suggesting that relative spatial location was incidentally encoded with their face stimuli, even though irrelevant for the completion of the task. A further experiment extended this finding to simple shape stimuli. Subsequent experiments indicated that a good reference frame should be similar in size to the TBR stimuli, and that even distracter items serve as good memory frames of reference. Interestingly, in their final experiment they demonstrated that verbal stimuli (letters) could be encoded independently of spatial location – that is, location change did not affect performance for these stimuli, suggesting the incidental encoding of spatial information is something that only applies to purely visual representations.

Finally, consistent with the idea of automatic encoding of spatial location during encoding of visual identity, Finke, Bublak, Neugebauer and Zhil (2005) compared
performance in two one-dimensional tasks (requiring memory for either random shapes, or spatial location) with performance on a two-dimension memory task, where both shape and location information had to be retained. Their results indicated costs associated with the two dimensional task which were asymmetric in nature. Specifically, maintaining location information (location one-dimensional task) suffered as a result of the additional demand of encoding shape (the two-dimensional task), whereas performance in their shape task was only slightly affected by the additional demand of encoding spatial information. In other words, the encoding of spatial information did not impose further demands on the encoding of shape information into memory. The authors reasoned that the lack of interference from the additional encoding demand indicated that the encoding of shape automatically resulted in the encoding of spatial location - no cost was incurred because the information was already encoded. It appears therefore that in encoding object identity, spatial location may be obligatorily encoded. This supposition makes sense from an evolutionary point of view since visual objects around us always appear in particular locations, and remembering locations of objects is integral to affording actions towards those objects. Furthermore, the close linkage between visual and spatial processes may underpin the discrepancy between findings noted in the behavioural dissociation studies, and the neuropsychological studies of independence between visual and spatial processing information (e.g., D'Esposito et al., 2000; Downing, 2000; Jiang et al., 2000; Nystrom et al., 2000; Olson & Marshuetz, 2005) discussed in Section 2.

Evidence demonstrating the association asymmetry does not easily fit with the idea that feature binding results in the creation of a new object or construct in memory. If shapes and locations are bound into an entirely new object, how could such asymmetries arise? The data are more consistent with the parallel storage account (e.g., Wheeler & Treisman, 2002), with the added proviso that links between the features may not be equally weighted, but can be uni-directional and contribute asymmetrically. Thus, feature A may be linked to feature B while the reverse relationship may not hold. Additionally, other lines of research have cited spatial location as serving a prominent role in visual cognition, rather than just as another visual feature to be bound in memory, (e.g., Hasher & Zacks, 1979), which may go some distance in explaining the binding asymmetries in memory described above. For example,

Hasher and Zacks (1979) asserted that the processing of spatial location does not require awareness or focussed attention, and furthermore can not be purposefully inhibited (see Mandler, Seegmiller & Day, 1977 for similar). This fits with the afore mentioned memory asymmetry data since in encoding visual attributes of an array, spatial location information would necessarily be encoded (c.f., Caldwell & Masson, 2001; Light & Zelinski 1983; Naveh-Benjamin, 1987; Park & Masson, 1982). On the idea of an asymmetrical contribution of visual and spatial features, in the field of visual perception, Navon (1977) proposed the Global Precedence Hypothesis. Using compound letter stimuli, results indicated that responding to the identity of the larger letter interacted with responses to the smaller letter more than was the case vice versa. This suggests that derivation of the larger letter occurs prior to the derivation of the smaller letter - that analysis of the global structure of the scene preceded the analysis of the local attributes within that scene (c.f., Kinchla & Wolfe, 1979). This hypothesis fits with findings in the memory binding literature, and is similar to the hierarchical encoding explanation put forward by Jiang et al. (2000) which suggests that the encoding of visual attributes of an array cannot be carried out without also encoding the relational spatial locations of those items first. Interestingly, one explanation of the Global Precedence Hypothesis has been attributed to spatial attentional selection. Under this formulation an attentional spotlight is biased toward global information on the basis of stimulus saliency, mediated by visual onsets which capture spatial attention and dictate the size of the spotlight which is initially spread over the visual scene (e.g., Stoffer, 1993). This global bias permits the fast analysis of the global attributes of the scene, but then needs to be shifted to local attributes in order to make more fine grained analysis of the visual scene. Thus analysis of the global may necessarily precede analysis of local attributes (see also Baylis & Driver, 1993 for similar).

In addition, theories of perceptual integration such as the Feature Integration Theory (FIT: e.g., Treisman & Gelade, 1980) suggest that spatial location may play a primitive role in feature binding. Given the degree of overlap between the fields of attentional selection, perception, and memory, and more specifically that in these fields, processing visual identity appears to encompass some encoding of spatial location, the following sections assess evidence from these divergent areas of research.

4.4. The Binding Asymmetry: Evidence from Attentional Selection and Perceptual

Integration

Evidence discussed so far suggests that visual and spatial features are registered and processed by the visual system through distinct specialised pathways (e.g., Ungerleider & Mishkin, 1982), and further that the two classes of information are processed and represented independently within working memory (e.g., Della Sala et al., 1999). Further, we have seen that this disparately processed information can be (albeit under certain circumstances) bound in memory providing some economy of storage (e.g., Wheeler & Treisman, 2002). Importantly, results from the memory literature suggest that visual and spatial features may contribute asymmetrically to the formation of bound representations. What follows is a review of evidence from the attentional selection and perception literature, which converge with the memory literature in suggesting that there may be an asymmetry in the encoding of shape and location information. Specifically, it may not be possible to register visual information in the absence of spatial information.

When confronted with a visual scene, there is undoubtedly more information present than is desirable, or necessary to subject to further processing. Selective visual attention is the mechanism through which task-relevant information is selected and task-irrelevant information is disregarded. Recent evidence from investigation into attentional selection is consistent with the idea that spatial location may be pivotal in the encoding of object identity. However, historically, there have been two competing formulations of the units of attentional selection.

According to the space-based view, visual attention is directed toward, and selects on the basis of, object-invariant locations, or regions of space within a visual array. Its operation has been likened to a spot-light (e.g., Broadbent, 1982; Posner, 1980), or a zoom lens (e.g., Eriksen & Yeh, 1985). Objects which fall under the focus of spatial attention are subject to further processing, while those outside of the beam are not. Conversely, proponents of the object-based view suggest that attention selects on the basis of location invariant objects, or perceptual groups of objects, which are parsed in accordance with Gestalt laws (e.g., Duncan, 1984; Neisser, 1967), for example: proximity (e.g., Banks & Prinzmetal, 1976) and similarity (e.g., Kahneman & Henik, 1977).

On the idea that spatial location serves a special function in visual selection, and that the encoding of object identity may necessarily involve the encoding of spatial location, the object-based and space-based views can be reformulated in the following way. The objectbased view proposes that *all* Gestalt principles are employed in order to segregate the visual scene into units for further processing. A key assumption of which is that any feature (e.g., colour, shape or proximity) can guide attention, and spatial location (or proximity) is not assumed to have any special role in selection. In contrast, the space-based view holds that proximity has special status in object selection, above and beyond selection by other features such as colour or shape. In short, the former supposes that spatial location along with other features, contribute symmetrically to processing, whereas the latter holds that there may be an asymmetry in the contribution of spatial-attention versus selection on the basis of other visual features.

Evidence for purely space-based selection has been found using a variety of paradigms including the cueing paradigm (e.g., Posner, 1980; Vecera & Farah, 1994); and the response competition paradigm (e.g., Eriksen & Eriksen, 1974). In the cueing paradigm, the focus of spatial attention is varied by pre-cueing the area within a visual array in which the target is likely to occur. Typically, target performance is contrasted between two cueing conditions. Valid cues are presented within the area the target subsequently will appear, whereas invalid cues direct attention to a location in which the target will not appear. The typical finding is that target performance is facilitated at the cued location, compared to target performance with invalid cues (e.g., Hoffman & Nelson, 1981; Lamy & Tsal, 2000; Posner & Cohen, 1984; Vecera & Farah, 1994). Thus prior knowledge of spatial location facilitates processing at that location. Under the spot-light formulation, the cue calls the 'beam' to a particular region of space. When the target appears in that cued location, as it still falls under the beam, it is processed with priority.

Support for the object-based view has been established using divided attention tasks (e.g., Baylis & Driver, 1993; Duncan, 1984; Vecera & Farah, 1994); the flanker response competition paradigm (Erikson & Hoffman, 1974); and selective looking (e.g., Neisser, 1967; among others, see Scholl, 2001 for a review). Results from the flanker response competition paradigm suggest that it is difficult to disregard distracting information when it appears as

belonging to a task-relevant object, or perceptual group of objects. On perceptual grouping, research has demonstrated more interference from distracters grouped with the target on some dimension (e.g., colour), than from un-grouped distracters (e.g., Driver & Baylis, 1989; Eriksen & Hoffman, 1974), even when grouped distracters appear farther from the target than non grouped distracters. The implication is that perceptual grouping (by movement or common colour for example) rather than spatial location (or proximity) limits selection across a visual scene.

A further line of research supporting object-based selection utilises divided attention tasks, which indicate a difficulty in attending to two objects simultaneously - a two-object cost. The pivotal demonstration of this was made by Duncan (1984). In Duncan's task, participants were presented with a box and a line appearing simultaneously (and superimposed) at the same spatial location. The box and the line had two properties each. The box was either short or tall, and had a gap in its contour at either the right or the left. The line was either presented tilting to the left or to the right, and could be dashed or dotted in texture. The task was to report two properties of the array. The finding was that participants were slower to report two properties belonging to different objects (i.e., one to the box, and one to the line) compared to two properties from the same object. The two object costs was interpreted as attention selecting location invariant objects, as, if attention was orienting to unparsed regions of space, such a cost would not arise (as both the box and the line appeared at the same spatial location, and according to the space-based view would be processed conjointly). The finding has been replicated numerous times, enduring manipulations of spatial separation (Vereca & Farah, 1994), and using identical one- and two-object arrays (Baylis & Driver, 1993), providing compelling evidence for the object-based view. There is little controversy therefore that attention can select from both space-based and object-based representations.

Recently, consistent with the memory literature, several lines of research have demonstrated that spatial location plays a special role in visual attentional selection (see Lamy & Tsal, 2001 for a review) providing a possible reconciliation of the two viewpoints. More specifically, spatial attentional selection appears to be important for the selection of object-features. For example, evidence suggests that object-based selection does not occur in a wholly space-invariant way (e.g., Kim & Cave, 2001); that spatial attention is deployed

even when irrelevant for completion of attentional tasks (e.g., Lamy & Tsal, 2000; Hoffman & Nelson, 1981; Kim & Cave, 1995); and that errors in tasks tapping selection for features other than spatial location (e.g., shape or colour) are often spatial in nature (e.g., Tsal & Lamy 2000). In addition, more stringent comparisons of object-based and space-based attention within single studies (e.g., Lamy & Tsal, 2000; Soto & Blanco, 2004) have led to a similar conclusion: that spatial location serves as more than another simple Gestalt unit for selection, and that the allocation of spatial attention may be necessary for the selection of object features.

Tsal and Lamy (2000: see also Hoffman & Nelson, 1981; Kim & Cave, 2001) demonstrated this attentional asymmetry in finding that attendance to any feature of an object entails the attentional selection of spatial location. Participants were presented with a circle array containing six different letters, each in a different colour (Experiment 2). Three of the (non-adjacent) letters were superimposed with three different geometric shapes, each differing in colour. The task was to report the shape relating to a given colour, and then as many letters as possible from the array. The critical comparison was between the *colour letter*, which comprised a letter in the same colour as the to-be-reported shape; and the *location letter*, which was the letter enclosed by the to-be-reported shape. Results indicated that location letters were reported more frequently than colour letters - spatial attention (although task-irrelevant) guided attention more than selection on the basis of grouped colour (which would predict prevalent report of colour letters).

Other lines of research demonstrating the special status of spatial location have used paradigms contrasting grouping effects (typically advanced as evidence for object-based attention) and spatial cueing effects in the same paradigm (e.g., Kim & Cave, 2001; Vecera & Farah, 1994). Kim and Cave (2001) assessed whether grouping by colour entailed some form of spatial selection. In their Experiment 1, the primary task was for participants to report a target letter, appearing at a known location. On each trial, three letters were presented, and the central letter was always the target. One of the distracters matched the target letter in colour (grouped distracter), while the other did not. On some trials, after the letters were no longer in view, a spatial probe appeared in one of the distracter locations. Participants were to make a speeded response to this probe. The authors reasoned that if selection is based

on spatially invariant grouped representations, probe response times would not vary with location. Conversely, if grouped objects were selected based on spatial location, responses to the probe appearing at the grouped distracter location should be faster than to probes at the ungrouped distracter location. Results indicated that response times were faster when the probed location appeared at the location of the grouped distracter, suggesting that perceptual grouping by non-spatial factors is mediated by spatial processing.

These results firstly suggest that grouping (initially provided as evidence for objectbased selection) is not space invariant, but moreover, that selection on the basis of nonspatial features is achieved through the allocation of spatial attention. Kim and Cave (2001) subsequently suggested their 'Object-directed Location Selection' hypothesis, which suggests that selection on the basis of non-spatial features (such as grouping by colour for example) can guide the allocation of attention to a location (or group of locations), which in turn enhances processing at that location (see also Vecera & Farah, 1994, for their conception of the 'Grouped Array Hypothesis').

Finally, Lamy and Tsal (2000) were among researchers who stringently contrasted space-based and object-based attention within a single task, and similarly found that attention selected grouped objects, in keeping with the object-based view, but that this was not done in a space invariant way, in keeping with the space-based view. Their results suggested that spatial location was attended whether or not space was task-relevant, whereas cued object features (e.g., colour or shape) were only attended when task-relevant (c.f., Soto & Blanco, 2004, who noted that spatial cueing effects and object cueing effects could occur even when space or object cueing was task-irrelevant, although the spatial cueing effect was larger in magnitude).

In sum, evidence presented so far suggests that visual attention can be allocated toward objects and space, but that the allocation of attention to visual objects is not done in a wholly space invariant way. Further, findings are broadly consistent with Kim and Cave's (2001) 'Object-directed Location Selection' hypothesis, which suggests that visual features other than spatial location can be the subject of attentional selection, by guiding (or capturing) attention to the location of those objects, in turn facilitating processing at the attended location. The special status of spatial location in visual attention therefore is apparent.

Consistent with the memory literature it appears that the spatial location serves an organizational role in visual cognition, permitting the direction of attention to objects, or groups of objects in visual arrays for further processing. Importantly, the allocation of attention to visual objects appears reliant on the representation of spatial location, even if irrelevant for the completion of the task. The memory asymmetry findings discussed in Section 4.3 could therefore be due to effects stemming from attentional selection.

Evidence for object integration in the field of visual perception is largely in agreement with the attentional selection literature, in that spatial location is often cited as having a special role. The binding problem in perception relates to how initially fleeting groupings (or bindings) between features are preserved so that they can be maintained for further action. For example, it is not enough to simply register the colour, shape and location of an item – one needs to be able to maintain all of these features in order to afford an action toward it. Binding in perception could therefore be viewed as the bridge between attentional selection and memorial binding (although it should be noted that perceptual binding and memorial binding differ to the extent that in the latter, participants are free to engage in mnemonic strategies).

A common theme underpinning perceptual accounts of binding is that these assemblies of features are entered into an 'object-file'. Kahneman and Treisman (1984) were among those pioneering the notion of the perceptual object-file (see also Kahneman et al., 1992; Treisman, 1993), which is a fully integrated episodic representation of a currently attended object. Object-files assume a special role for spatial location in that they are initially addressed solely on the basis of spatial coordinates (Kahneman et al., 1992). Attendance to spatial location is therefore critical in object-file formation, and while the object remains in view. However, once an object is no longer in view, spatial location information is no longer critical, and instead, the object file can be addressed by any of its features, including spatial location (Treisman, 1992). Additionally, in order to allow coherent object perception, objectfiles are 'sticky', such that they can track a moving object, provided that the movement is perceptually plausible. Object-files therefore serve to allow us to ascertain which features (the 'what') went with which object, on the basis of spatial location (the 'where').

Evidence in favour of perceptual object-files has been found in negative priming

experiments (e.g., Allport, Tipper & Chmiel, 1985), and in experiments using the reviewing paradigm (e.g., Hommel, 1998; Kahneman et al., 1992; Treisman 1993). Using the former, Allport et al. (1985) presented participants with pairs of coloured, superimposed letters. The target was defined by colour, and the task was to identify the letter possessing the target colour (the other letter served as a distracter). Results indicated slower response times for identifying the letter when the current target matched the preceding distracter letter. The authors asserted that target and distracter features were automatically integrated into an object-file type association. Subsequently on the following trial, when there was a mismatch in association between stimulus features, responding was impaired as a new object-file had to be formed. Conversely, if the same combination of letter and distracter was presented again, performance was facilitated by the already existing object-file created on the previous trial.

In the reviewing paradigm, evidence typically indicates that responding to a letter which matched one in a preview display is facilitated if that letter also appears in the same (absolute or relative) location (Hommel, 1998; Kahneman et al., 1992; Treisman, 1993). For example, Kahneman et al. (1992) presented participants with a preview letter display, followed by a single probe letter, for identification. Their results indicated that response times were faster when the letter was repeated between preview and probe (i.e., a priming effect), but that response times were faster still when the probe letter matched the identity *and spatial location* of a letter in the preview array. This finding suggests that on encountering the preview display, object-files containing letter identity and spatial location were formed. If the probe matched an already created object-file, performance was facilitated compared to no match, or to a partial match, where a new file would need to be created.

The object-file concept has been investigated extensively over the years, with recent evidence suggesting that object-files can persist for up to 8 seconds (Noles, Scholl & Mitroff, 2005), that they cannot 'stick' to a split object (Mitroff, Scholl & Wynn, 2004); and that object-file formation is not analogous to conscious perception (Mitroff, Scholl & Wynn, 2005) whereby the tracking of an object-file can occur independently of what participants report to perceive. This latter point is of particular interest since it suggests that binding in perception occurs without knowledge from the perceiver, and thus may be an automatic process.

In summary, the object-file formulation suggests that encountering a visual object

results in the creation of an object-file: a high-order representation containing all information about a visual object, addressed on the basis of spatial location. However; the full perceptual integration of object features has not been fully supported by empirical evidence. For example, Hommel (2004) demonstrated that object features typically enter into binary bindings, rather than higher-order bindings between all features of an object. In addition, Hommel (1998) found evidence that action related response information can be integrated with visual stimulus properties (see also Hommel, 2004; Hommel & Colzato, 2004; Treisman, 1992). Further, evidence does not always agree with the idea that object-files can be addressed solely on the basis of spatial location. For example, in developmental research, experimentation indicates that infants can address object-files by non-spatial (changes in) feature information (see also Hommel, 1998).

A further criticism of the object-file formulation is that it cannot account for object-non specific priming effects (Hommel, 2004). Object non-specific priming effects refer to where the repetition of one (visual) feature of an object can facilitate performance in the absence of repetitions of other features (see Gordon & Irwin, 1996; Hommel & Colzato, 2004). According to the object-file formulation, priming one feature involves priming the entire object (predicting object-specific priming effects).

In the light of such evidence, Hommel (2004; see also Hommel, 1998; Hommel & Colzato, 2004) proposed an event-file account of perceptual binding. An event-file is: "...a network of bindings that temporarily link codes of the relevant or salient features of the perceptual event, an accompanying action, and the task context" (Hommel, 2004; pp. 1).

Hommel (2002) elaborated on the event-file construct, finding evidence that the creation of bindings including response related information takes time, and does not occur before 500ms (see also Kahneman et al., 1992), further the percept could be maintained for a minimum of 4 seconds, even in the absence of visual input from the object, suggesting that event-files can be maintained in memory. Hommel and Colzato (2004) further suggested that the outcome of an event file is, in part, determined by task goals influenced by top-down support from working memory. Hommel (2004) noted that the retrieval of one or more of the bound features retrieves the event-file, but that this is not constrained to the retrieval of location information. Spatial location may play a key role in the creation of an event-file

(consistent with the attentional selection literature), but may not be integral to its retrieval (explaining why the files can be accessed by features other than spatial location).

In summary, perceptual accounts of integration either propose that all features are entered into a fully represented object-file (e.g., Kahneman et al., 1992), or that top-down control and feature salience can mediate which features are entered into an 'event-file' (e.g., Hommel, 2004). Both theories suggest that spatial location plays an important role in integration, at least in the formation of object-files, if not for their retrieval. Clear parallels can be drawn between the attention literature and the perceptual literature. While perceptual binding supposes that spatial location is an important mediator for feature integration, the attentional selection literatures suggests that spatial location is not just essential for integration, but also for item selection.

One influential model of perceptual integration which fits with the aforementioned 'file' accounts is Treisman's Feature Integration Theory (FIT: Treisman & Gelade, 1980; Treisman, 1998). In terms of the dichotomy between object-based and space-based attentional selection, FIT is primarily a space-based selection model, according to which focal attention provides the glue which holds bound representations together (Treisman & Gelade, 1980).

The model assumes that individual visual features are initially processed independently within the cognitive system (e.g., Bartels & Zeki, 1998), and that each feature type is represented by a feature map. Conversely, a master map of locations represents regions of space, without representation of the features within those regions. The model is illustrated in Figure 2. In order to integrate object features, the feature maps signal whether a particular feature is present in the visual field, then the master map of locations is scanned by a scalable window of attention which checks for currently active features within the feature maps, within a particular location. Other features from irrelevant locations are suppressed in order to avoid erroneous binding. Finally, integration can be guided by long-term knowledge: if an object is consistent with an existing representation, features are unlikely to be erroneously bound.



been Once features have registered, they are entered into an 'object-file' (e.g., Kahneman et al., Hommel. 2004) 1992. c.f.. as discussed above. Tasks which do not require integration can be solved by checking the feature maps for flags signalling the presence of that feature, and do not require attention. In other words, the detection of a single feature is thought to occur pre-attentively. Conversely, correctly associating a combination of visual features requires serially applied focussed attention, and

the retrieval of connections between the features maps and the master map of locations.

A key prediction of FIT is that in the absence of focal attention, binding errors (or illusory conjunctions) should be observed. Illusory conjunctions are the incorrect pairings of perceived features (for example, if a blue square and a red triangle are presented in a TBR array, and at test, participants report the presence of a red square; or a blue triangle). Importantly, in report of illusory conjunctions, feature information (flagged by the feature maps) is correct, however, the binding of these features is incorrect. Consistent with FIT's account, the occurrence of illusory conjunctions is high in situations where spatial attention is diverted and with brief presentations of TBR items (e.g., Prinzmetal, Presti & Posner, 1986; Prinzmetal, Diedrichson & Ivry, 2001).

Illustrative of both of these points is the work of Treisman and Schmidt (1982), who presented four shapes of varying colour, size, and format arranged at the corners of a square, flanked on each side by black digits. The task for participants was to report all features of the shape in one of the four corners, cued after the presentation of the display. Their findings indicated illusory conjunctions at rates above levels attributable to guessing alone. Consistent with FIT, results were interpreted as a direct result of the prevention of focussed attention on the stimuli, since the TBR array was presented briefly (200ms), and the stimuli (and flanking letters) were spread out across the screen, resulting in a global spread of attention. In addition, in a further experiment, the same test stimuli were used but the relevant item was cued 150ms before the array, allowing focussed attention on the task-relevant item. Under this pre-cueing condition, illusory conjunctions disappeared to a level no higher than predicted by guesswork.

Additionally, evidence implicating the importance of focussed spatial attention in holding object features together has been noted in brain damaged patients. For example, stroke patients with unilateral visual neglect can only direct visual attention to one side. Report of stimuli presented in the unattended side results in high rates of illusory conjunctions (Cohen & Rafal, 1991). Further, in a condition referred to as Balint's syndrome, bilateral parietal damage patients are unable to locate objects in space, suggesting a loss of spatial representation. Consistent with FIT, these patients report more illusory conjunctions than controls, which, according to Treisman (1999) was due to a loss of the master map of locations. Research into illusory conjunctions therefore supports the importance of spatial attention for the correct perceptual integration of object features.

Research using the visual search paradigm has also found evidence consistent with FIT, and the notion of the importance of focussed attention for feature integration. Accomplishing a visual search task involves isolating a pre-defined target from surrounding distracters, which typically comprise simplified visual stimuli (e.g., coloured letters: Treisman, 1996). Search tasks can be manipulated so that they do or do not require the integration of features. FIT predicts that locating targets that vary on a single feature (e.g., searching for a blue 'T' among red 'T's') can be achieved by checking the feature maps for flags. In other words, the task can be solved pre-attentively. Conversely, locating a conjunction of features (e.g. a blue 'T' among blue 'Xs' and red 'Ts') requires the serial application of focussed attention so that the attentional window can scan the master map of locations, addressing the feature maps in order to see which visual features go together within the array. Consistent with these predictions, Treisman and Gelade (1980) demonstrated that searching for a conjunction of features resulted in search times which increased linearly with the number of distracters present in the array. Conversely, search for a single feature resulted in search

times independent of the number of present distracters. Further, Treisman (1986) demonstrated that target pre-cueing facilitated performance in conjunction searches, but had less of an effect on single feature searches.

Although FIT has been successful in accounting for visual search and illusory conjunction data, other data have proven to be difficult to reconcile under the framework in its original form. Evidence suggests that conjunction searches can be solved pre-attentively under some circumstances. For example, Enns and Rensink (1991) demonstrated pre-attentive binding in a search task, whereby participants had to search for targets differing in three-dimensional orientation from distracters (see also Ramachandran, 1988). In response, Treisman (1993) suggested that 'pop-out' (facilitated pre-attentive search) occurs when the attentional window is broadly focussed, rather than being narrowly focussed. This global spread of attention can result in perceived pop-out of some conjunctions of features.

In sum, as in the attention literature, perceptual binding can be mediated by spatially directed attention. Within the context of previously discussed research on the object-file formulation and perceptual integration, spatial location appears to play an all important role, consistent with the memory asymmetry literature and the attentional selection literature. One further assertion of the perceptual binding literature is that focussed attention forms the 'glue' which holds features together. We now turn to discussion of the episodic buffer component of the Working Memory Model (Baddeley, 2001), which holds a similar role for attentional binding in memory. Furthermore, evidence discussed pertaining to binding in memory highlights the necessity of further explanation within the Working Memory Model (Baddeley & Hitch, 1974) for integration processes.

5. Binding, the Episodic Buffer and Focussed Attention

Evidence discussed to date suggests that visuo-spatial information can be bound together, enhanced by perceived unitariness; that object parts can be integrated, although less well than properties of an object, and that the binding between visual and spatial attributes appears to be asymmetric such that the encoding of spatial location is a pre-requisite to the encoding of visual identity, while the reverse relationship does not hold. Corresponding effects have also been noted in the perceptual and attentional selection literatures. It is clear that the WM model (Baddeley & Hitch, 1974) in its original form (discussed in Section 3) was unable to account for such findings, particularly since visual and spatial information were proposed to be processed in separable subcomponents of the VSSP.

In order to account for visuo-spatial binding (along with other phenomena in the verbal domain), the episodic buffer was proposed as a fourth component of the WM model. On the lack of explanatory power of the original model for binding, Allen, Baddeley and Hitch (2006) noted that "This omission is particularly obvious when the relevant information is stored in different subsystems, or when binding involves access to long-term memory, but applies equally well when all the relevant information is stored in a single subsystem." (Allen et al., 2006, pp. 1). The revised WM model is illustrated in Figure 3.



Figure 3. The current version of the Working Memory Model (Baddeley, 2001).

The episodic buffer is assumed to be a temporary storage system for integrated information originating from either the two slave systems, or long-term memory. In this sense, it is an interface between memory systems, which represents information in a common *multi-*

dimensional code. Importantly, the resulting representation under this formulation is a fully represented object. The buffer is assumed to be under the attentional control of the central executive, which retrieves information through conscious awareness, or focussed attention, and is limited in capacity to the extent of available CE resources (Baddeley, 2001). Accessing the buffer can only be achieved via the CE, and as such a key limitation to the maintenance of bound representations, according to the model, is that they are heavily dependent on CE attentional resources. Neural correlates for the episodic buffer have been noted in brain imaging studies (e.g., Prabhakaran et al., 2000). The Prabhakaran et al. (2000) method was developed to specifically explore binding between verbal and spatial feature dimensions in working memory. In the bound condition, upper case letters were placed within locations marked by parentheses. In the separate condition, participants were presented with four locations marked by parentheses, and four letters which appeared in a row at the centre of the screen. At test, for both conditions, participants were presented with a single lower-case letter in a location, surrounded by parentheses. The task for both of these conditions was to indicate whether the location and the letter of a single probe item had been present in the TBR array, regardless of whether they had been presented together. Their results indicated domain specific activation in the separate condition, but additional right frontal activation in the bound condition, consistent with the role of the frontal cortex for binding. The authors asserted this latter activation as evidence for the existence of a buffer in memory for bound representations, consistent with the episodic buffer framework (see also Simon-Thomas, Brodsky, Willing, Sinha and Knight, 2003).

Other authors (e.g., Ruchkin, Grafman, Cameron & Berndt, 2003), however, have argued that this activation may better be characterised by the right prefrontal cortex playing a role in the process of maintaining binding information in an active state. Thus, rather than representing a new storage module for bound representations, the frontal activation may represent the maintenance of links between features (Ruchkin et al., 2003), with the features themselves stored in parallel consistent with the parallel storage account (Wheeler & Treisman, 2002).

We have already seen that the buffer in its current form has difficulty accounting for evidence of asymmetries in association between visual and spatial information. If the result of

binding processes is the creation of an entire new memory object to be stored in the buffer, how can it be that such asymmetries arise? Additional direct experimentation as to the nature of the binding asymmetry between visual and spatial features may provide useful constraints on the development of the episodic buffer.

One key claim of the buffer which can be assessed is whether binding in memory is heavily dependent on attentional resources. Experimentation to date has led to mixed results. For example, while some authors find that binding is indeed dependent on available attentional resources (e.g., Wolfe, 1999; Wheeler & Treisman, 2002), others have failed to find such an effect (e.g., Allen et al., 2006). Allen et al. (2006) acknowledge that there may be a distinction between automatic binding processes, and attention demanding binding processes (which take place within the episodic buffer), but as of yet, the conditions conducive to automatic versus effortful (controlled) binding remain unclear.

In terms of perceptual binding, support for the supposition of the necessity of focussed attention can be found. For example, we have already seen that in order to perform adequately on a visual search task for a conjunction of features, focussed (spatial) attention must be applied to each item serially - thus the search is achieved attentively (see FIT: e.g., Treisman & Gelade, 1980). Furthermore, evidence suggests, consistent with FIT that in the absence of focussed attention, binding errors (or illusory conjunctions) are prolific (e.g., Prinzmetal et al., 2001; Prinzmetal et al., 1986; Treisman & Schmidt, 1982). Research into binding in memory also implicates the role of focussed attention in binding. For example, Wheeler and Treisman (2002) found a decrement in performance on their probe recognition task when a 'whole-display' probe was used, which disappeared (and additionally supported integration) when a 'single-probe' was used (Experiment 4B). The authors stated that binding within memory, along with binding in perception, may depend on focused attention, which was distracted in the whole-display tests, and consequently caused bindings to 'fall apart' (see also Wolfe, 1999). Similarly, Stefurak and Boynton (1986) found that while memory for separate features was good (silhouettes of animals or respective colour), memory for conjunctions of these features was comparatively poor under an attentionally demanding concurrent task, supporting the role of attentional (executive) processes in memory for binding.

The potential involvement of attentional processes in the formation of bindings has been supported in neuropsychological research. Investigation of the CE indicates the involvement of the prefrontal cortex (e.g., Baddeley, 1986). Further, Baddeley (2001) in commentary of the episodic buffer noted that the prefrontal cortex may be important for both the central executive and the episodic buffer. Consistent with this supposition are the results of Prabhakaran et al. (2000) who noted right frontal activation for the maintenance of bound verbal-spatial associations, consistent with the role of the frontal cortex for binding.

More relevant to the current review, Simon-Thomas et al. (2003) carried out a recognition study while measuring brain activity by way of event related potentials. Their experiment measured activity while participants carried out a visual task, a spatial task, and a combined visual-spatial task. In their visual task, participants indicated whether a visual object (not varying in location) matched one of the TBR items. In their spatial task, participants indicated whether a spatial task, participants indicated whether a spatial location (marked by a grey patch) matched a TBR item, and finally, in their integrated task, participants judged whether a probe item matched a TBR item in both identity and spatial location. The behavioural data indicated superior performance in the integration task relative to the visual and spatial tasks. The ERP data for the separate visual and spatial tasks were in line with the 'what' and 'where' pathways respectively discussed in Section 2.2. Furthermore, the 'what' and 'where' pathways were activated during the integration task, but with the additional activation of frontal-parietal networks, supporting the involvement of executive processes in the integration of stimuli.

However, not all evidence is consistent with the essential role of attention for binding. For example, Allen et al. (2006) attempted to identify conditions under which executive involvement is critical for the binding of features in visual working memory, using a paradigm based on that used by Wheeler and Treisman (2002). They noted that in Wheeler and Treisman's study (2002) the same presentation format was used across single feature and integration conditions, such that the same information could be encoded in all conditions. To overcome this possible limitation, using colour and shape as visual stimuli, Allen et al. (2006) adapted their methodology.

In their Experiment 1, in the shape task, they presented participants with four shapes all in a single colour. At test, participants had to decide whether a single shape represented

one from the TBR array. In their colour condition, they presented four coloured squares, and participants judged whether a single probe square represented a colour present in the TBR array; in their combination condition, they presented four coloured shapes, and at test participants judged whether a single probe represented an original colour-shape combination. Importantly to test binding, they included probes whereby a shape and colour had been repaired. Finally, in the either condition, they presented four coloured shapes, and participants did not know which feature would be tested until test. Their results indicated a binding effect such that memory performance did not differ between the single feature shape condition (the more difficult of the two single feature conditions), and the combination condition.

In their second experiment, they sought to find out whether the binding noted in Experiment 1 was automatic or effortful. To assess this they paired their tasks with an attentionally demanding secondary task – counting backwards in 1's. Results indicated again a binding effect where memory in the combination condition was as accurate as in the shape single feature condition (the harder feature). However; the attentionally demanding task did not affect performance in the combination condition more than it affected the single feature conditions (the detrimental effect of the secondary task was uniform across conditions).

In their third and fourth experiments they again failed to find an effect of attention on binding using more difficult concurrent tasks: a near span recall of a string of digits concurrently and counting back in 3's, respectively. Their results unequivocally indicated that the binding between colour and shape did not depend on executive processes any more than single features, and could be carried out relatively automatically.

In their final experiment, they sought to test another potential explanation as to why Wheeler and Treisman (2002) found a detrimental effect of using a 'whole-display' test relative to a single probe, which did not encompass focussed attention. For this, they compared simultaneous item presentation with sequential item presentation. Under these conditions they found that memory in the combination condition was significantly worse under sequential presentation than simultaneous presentation, suggesting that rather than being dependent on attentional resources, binding between colour and shape is fragile and susceptible to direct interference from subsequently presented items. The authors concluded that automatically bound information is naturally fragile and can easily fall apart when

subsequent items are presented. In sum, it appears that not all binding requires focussed attention.

Within the context of the aforementioned review of binding in Section 4, and the unitisation effect, it must be noted that Allen et al.'s (2006) stimuli constituted property binding, and as such features may be bound automatically as a result of being properties of the same object. However, this does not rule out the possibility that other types of binding in memory require attentional resources. Indeed, Allen et al. (2006) acknowledge this fact, and that different types of binding exist in discussion of their results. It may be the case that part binding for example (Xu, 2002a; 2002b) requires attention. More relevant to the current review, we have also already seen that location binding may represent a functionally different type of binding than property binding by virtue of asymmetries in contribution of visual and spatial features. As such, it remains an open issue as to whether binding to location requires focussed attention.

6. Rationale

This thesis was designed to examine the nature of integrated visual and spatial representations in VSWM guided by the following theoretical aims. The first aim was to demonstrate location binding using a paradigm which is less susceptible to alterative explanations (e.g., Luck & Vogel, 1997), such as parallel storage in the absence of binding. Specifically, the paradigm across all experiments will be based on adaptations of the single probe change detection paradigm used by Prabhakaran et al. (2000), only with visual and spatial features rather than with the verbal and spatial stimuli used in the original study (described below).

The second aim was to examine the temporal dynamics of location binding, which to date have not been systematically investigated in the literature. While research cited in the introduction has begun to touch upon the issue of location binding in memory, many of those studies, and indeed many of the studies investigating memorial feature binding in general, have typically used a fixed lag interval, which does not allow the tracking of the time course of bound representations. The importance of establishing the temporal dynamics of location binding speaks to two issues. Firstly, location binding may be a dynamic process, taking time to emerge, relevant to the issue of the automaticity of binding in memory. Secondly, bindings may 'dissolve' quickly, relevant to the issue of the demands of maintaining bound representations. To this end, all experiments presented (with the exception of Experiment 1A) included a variable lag interval between the TBR array and the probe display.

The third aim was to examine whether binding between visual and spatial features occurs automatically or whether binding is dependent on attentional resources. More specifically, the thesis examined whether feature binding in memory occurs as a result of task goals (e.g., do both features need to be task-relevant in order for binding to take place?). If binding is mediated by task goals, this may reflect some economy of processing within VSWM through which only task-relevant information is encoded. However, if binding proceeds despite task goals, one may argue that it is a relatively automatic process, consistent with that proposed in the perception literature (e.g., Kahneman et al., 1992). As previously noted, the contribution of focussed attention to binding still remains an open question in the literature, and in order to progress our understanding of binding in memory, conditions conducive to

effortful binding versus automatic binding should be established.

The final aim was to establish what the products of location binding are. Specifically, when visual and spatial features are bound together, do they form a whole new 'object' representation (as implied by the episodic buffer formulation of binding in WM; Baddeley, 2001), or do visual and spatial features become integrated by virtue of links between features that are stored independently (e.g., Ruchkin et al., 2003; Wheeler & Treisman 2002) which may in turn contribute asymmetrically to binding (Jiang et al., 2000; see also Olson & Marshuetz, 2005)?

7. Series Overview

Across the experimental series, variations of the Prabhakaran et al. (2000) paradigm were used. In its original context, this paradigm was developed to explore binding between verbal and spatial feature dimensions in working memory, using fMRI to isolate areas of brain activation responsible for the maintenance of bound representations. Within one condition, probes could either be made up of a letter that was in location (intact probe) or a letter and a location that were both in the array, but were not seen together (re-paired probe). In both cases, participants had the task of indicating whether the probe represented both a shape and location they had seen before in the TBR array. The paradigm is an interesting one from the point of view of binding in WM since the task demands are such that participants are required to endorse re-paired probes, which typically, in other memory research into binding have been used as foils (e.g., Wheeler & Treisman, 2002). Prabhakaran et al. (2000) found that participants were significantly faster and more accurate in responding to intact relative to re-paired probes. This was argued to reflect the retention of information in an integrated format. The authors suggested that the decrement in performance for re-paired probes reflected the need for participants to decompose their already bound-together memory representations in order to find a match. The implication of this latter finding is that for visually presented verbal information in this paradigm, spatial location and visually presented verbal information were subject to binding processes. The current series of experiments capitalises on the intact versus re-paired probe comparison, only using visual and spatial stimuli.

One further novel point of interest from our adaptation of this paradigm is in assessment of negative probe performance, (probes which require a 'no' response). Along with intact and re-paired probes, we contrasted performance between a both-feature-new condition, a new-shape (old location) condition and a new-location (old shape) condition. Although these trials were initially included as filler trials, performance differences between these trial types was informative on which feature (visual or spatial) contributed most to the probe decision. To our knowledge, this series of experiments constituted the first of its kind to assess negative probe performance in this way, and highlight the utility of this kind of approach.

In the present series of experiments, the presentation procedure remained the same: three irregular shapes were presented simultaneously (with the exception of Experiment 1A, where they were presented sequentially) in different locations in the TBR array, followed by the presentation of a single probe item. Critical probes were *intact* probes (a shape in location, as in the TBR array) and *re-paired* probes (a shape presented in a location presented, which had swapped places from the TBR array), and both always required a positive 'yes' response (probes requiring a 'no' response were also included). As previously noted, any processing advantage of intact probes over re-paired probes would be consistent with the idea that shape and location features had been bound in memory, since the feature proves to be superior to re-paired probe performance, the data would be consistent with binding in memory rather than the independent storage of features, which would predict no difference between the two probe types.

7.1. Series 1: Location Binding in VSWM

Series 1 was motivated by the need to demonstrate location binding, and utilised the Prabhakaran et al. (2000) paradigm. In Experiment 1A, TBR items were presented sequentially, whereas (guided by findings in Experiment 1A) in Experiment 1B, TBR items were presented simultaneously. In both experiments, participants were to report whether a single probe represented both a shape and location present in the TBR array. As the featural demands of both intact and re-paired probes were equivalent (i.e., both contained a shape and a location seen before in the TBR array), an advantage of recognising intact probes would be consistent with the idea that the shape and location features were bound together, as opposed to participants maintaining individual 'lists' of features (which would predict no difference between intact and re-paired probe recognition). The predicted decrement in performance for re-paired probe recognition compared to intact probe recognition is formulated as the necessity to decompose the bound memory representations in order to find a match for re-paired probes – we call this the binding effect. Probes consisting of foils were also used, requiring a 'no' response (see the method section for details). The second aim of Series 1 was to address the issue of the temporal dynamics of location binding, in order to

determine whether binding to location takes time to emerge, or whether the bindings formed are characterised by short-lived codes. In order to address this aim, Experiment 1B included a variable blocked lag interval between the presentation of the TBR array, and the probe. The lag intervals were set at 250ms, 500ms, 2000ms and 4000ms post stimulus offset.

As both features were task-relevant in Series 1, it was not possible to determine whether binding resulted in the representation of whole new objects in memory, or whether it was better described by links between separately stored features. Both views predict that there may be a decrement in performance for re-paired probes as a result of the need to decompose the object based memory representation on the former, or the need to sever links formed between features in the latter. Series 2 was designed to address this issue more directly.

7.2. Series 2: Location Binding - Asymmetrical Feature Links?

Experiments 2A and 2B sought to answer the question of whether visual and spatial features are integrated as a function of task goals, or whether they are integrated automatically. Further, the design of Experiment 2 allowed the assessment of whether the binding of visual and spatial features results in a whole new percept, or rather, if it is better characterised by links between features that contribute asymmetrically to binding. In Experiment 2A, participants were instructed to attend to and remember shapes only, while ignoring locations. A binding effect here would be consistent with the idea that intention to bind is not a necessary prerequisite for binding to take place when focusing on shape features. In Experiment 2B, participants were required to attend to and remember only If evidence for binding is gained in both location features, while ignoring shapes. experiments, the results would be consistent with the idea of a complete integration of shape and location features in our paradigm, and that the binding occurs automatically, that is, is not dependent on feature relevance or task demands. Conversely, if evidence for binding is present where participants are instructed to focus on shape features (Experiment 2A), but is not present where participants are instructed to focus on location features (Experiment 2B), evidence would have been gained for an asymmetry in the association of shape and location features, in line with recent research (e.g., Jiang et al., 2000), and would suggest that binding

may be better characterised by links between features stored in parallel (e.g., Ruchkin et al., 2003; Wheeler & Treisman, 2002) rather than the creation of a whole new object representation.

7.3. Series 3: Investigating the Binding Asymmetry

Series three was designed to assess more systematically what causes the binding asymmetry between shape and location features. In order to assess this, the relative encoding and maintenance difficulty of shape features was manipulated. Performance was contrasted between an easy-to-remember shape set and a hard-to-remember shape set in a shape-relevant experiment (Experiment 3B) and a location-relevant experiment (Experiment 3C). The experiments assessed a key assumption of the hierarchical account of the binding asymmetry (Jiang et al., 2000), namely, that in encoding object identity (shape) spatial location becomes automatically integrated (linked) by virtue of being encoded first. As such, increasing the attention allocated to the shape stimuli should also benefit the location stimuli by virtue of their close relationship. In short, as more resources are allocated to shape stimuli, these should also be shared by the location stimuli, increasing the size of the binding effect relative to less demanding shape stimuli. Conversely, as spatial locations are assumed to be encoded in isolation of the shapes occupying them (i.e., due to hierarchical processing dictating that the spatial configuration of the scene is derived first), manipulating the encoding demands of the shape stimuli should have little or no effect on the lack of binding in that location-relevant task. Statistically therefore, the hierarchical encoding account of the binding asymmetry predicts a main effect of binding, and an interaction between binding and shape difficulty in the shape-relevant task (Experiment 3B), but no main effect of binding, or an interaction between shape difficulty and binding in the location-relevant task (Experiment 3C).

7.4 Series 4: Is Location Binding Attentionally Demanding?

In the light of the newly proposed episodic buffer component of the WM model (Baddeley, 2001); Series 4 was designed to establish more directly whether binding to location occurs automatically, or whether it is dependent on focussed attention. We have already seen compelling evidence that at least some forms of binding (i.e., property binding) can proceed in the absence of focussed attention (e.g., Allen et al., 2006). However, whether

binding to location (which appears functionally different to other types of binding) requires the application of focussed attention remains an open issue.

The procedure followed that used in Experiment 1B (Series 1) with the addition of an attentional load condition. In the latter, participants were required to retain a string of digits during the encoding and maintenance of the TBR array. Accuracy on the load task was tested after the probe task by way of a digit probe, where participants were to report 'what came next' in the sequence they were maintaining. The load task was thought to place heavy demands on attentional processes by virtue of the fact that not only did it require retention of 4 digits, but also retention of the serial positions of each digit in order to perform accurately on that task (Lavie & de Fockert, 2005). If location binding relies on attentional resources, a loss of binding (e.g., equivalent intact/re-paired performance, or reduced binding effect) should be noted. However, if location binding can proceed in the absence of focussed attention, binding would be predicted in both the load and control conditions. Additionally, Series 4 allowed some investigation of whether the binding effect noted in Series 1 was a relatively automatic process, or whether it was effortful, perhaps by virtue of strategic processing.

SERIES 1: BINDING IN VSWM

8. Series Introduction

Series 1 aimed to demonstrate location binding in an adaptation of the Prabhakaran et al. (2000) paradigm used initially to study the integration of verbal and spatial features. In Experiment 1A, TBR items were presented sequentially, whereas in Experiment 1B, they were presented simultaneously. In both experiments, the task was to judge a single probe item in terms of both visual and spatial attributes. The critical comparison, indicative of binding, was between intact and re-paired probes. An advantage of intact probes over repaired probes would constitute evidence for binding by virtue of the fact that the two types of probe are equivalent on the feature level and only differ to the extent that their constituent features were or were not part of the same object in the TBR array. Both binding through the creation of a new object percept in memory, and binding by virtue of links between features stored independently predict that there should be some cost in decomposing bound representations in order to find a match for re-paired probes.

Previous research into the integration of visuo-spatial features suggests that binding effects are most pronounced where features to be integrated form properties of the same object (e.g., Ceraso et al., 1998; Delvenne & Bruyer, 2004; Walker & Cuthbert, 1998), the so-called unitisation effect. In addition, unitisation effects are most prominent in the absence of verbal recoding (which is assumed to be able to support between-object associations; Delvenne & Bruyer, 2004). Across Experiments 1A and 1B, intact probe features appeared as part (and indeed as properties) of the same object. In order to ensure the best chance of integration for our visual and spatial features, two controls were implemented to ensure visual processing: both experiments included an articulatory suppression condition; and the shapes used in both were difficult-to-name, irregular polygons, piloted previously to this end (Chuah, Maybery & Fox, 2004).

The second aim of Series 1 was to assess the temporal dynamics of location binding by including a variable lag interval between the presentation of the TBR array and the probe display (Experiment 1B). Within the literature on perceptual binding, evidence indicates that integrated precepts can persist for up to 8 seconds (Noles et al., 2005). Additionally, evidence

indicates that bound perceptual representations can be maintained for a minimum of 4 seconds in the absence of visual input from the object, suggesting a role for memory (Hommel, 2002). However, the issue of the persistence of bound representations in memory has not been directly assessed in the literature to date. The present study constituted, to my knowledge, the first systematic investigation of the temporal dynamics of location binding using this paradigm.

In sum, Series 1 attempted to establish the utility of the Prabhakaran et al. (2000) paradigm for the investigation of visual to spatial binding, and further to gain insight into the temporal dynamics of the binding process.

9. Experiment 1A

Guided by previous research suggesting that unitisation type effects are conducive to situations where features are perceived as belonging to the same object (e.g., Ceraso et al., 1998; Delvenne & Bruyer, 2004; Walker & Cuthbert, 1998), and binding effects are most prevalent when features to be bound are simultaneously available for encoding (Ceraso et al., 1998), TBR items in Experiment 1A were presented sequentially (i.e., simultaneous presentation may result in a bound representation of all objects in the array). In addition, in order to capitalise on any unitisation type effects which may be present for our shape/location stimuli, and to ensure visuo-spatial processing, two safeguards were used to ensure that our visual stimuli were not recoded verbally. Firstly, Experiment 1A included an articulatory suppression condition whereby participants were required to repeat the words 'one-two' out loud during the presentation of TBR items and during a retention interval. The articulatory suppression condition was included on the premise that in removing the capacity for participants to encode items verbally, unitisation effects may be more pronounced (e.g., Walker & Cuthbert, 1998). Secondly, the visual stimuli comprised of 16 irregular black polygons, previously piloted in order to be difficult to attribute verbal labels to (Chuah et al., 2004). The spatial stimuli consisted of a fixed set of 16 locations arranged irregularly on the screen in order to reduce the possibility of attributing verbal configuration tags.

The basic paradigm involved the presentation of three shapes in locations within a frame. The array was then followed by a single probe item which participants had to judge in terms of both visual and spatial attributes. There were two critical probe types – *intact probes* (a shape in location as seen in the TBR array) and *re-paired probes* (a shape in a location originally presented with another shape in the TBR array). Participants had the task of indicating whether the probe item comprised *both* a shape and location seen before in the TBR array, whether or not the features were initially components of the same object. Consequently, both the visual and spatial aspects of objects were task-relevant in Experiment 1A, and both intact and re-paired probes required a 'yes' response. Probes requiring a 'no' response were also included, varying in the extent to which they represented a new (not seen before on that trial) shape, a new location, or both a new shape and a new location.

Binding was judged to be indicated by an intact over re-paired probe advantage in

performance. As the demands placed upon memory at the feature level were equivalent between these two probe conditions, any difference in performance must be due to binding. Equivalent performance on these two probe types, however, would be more consistent with the idea of independent feature storage.

9.1. Method

Participants. Forty-eight volunteers participated in the 30 minute experiment for course credit, or for a small honorarium. Twenty-four participants took part in the control condition and twenty-four in the articulatory suppression condition. All participants reported normal or corrected-to-normal colour vision, and all were naïve to the aims of the experiment.

Materials. Stimuli were presented on a 14" computer screen of a Hewlet Packard Vectra (Pentium III) computer running Windows XP. The task was purpose-written using E-Prime. All responses were collected via the keyboard. Irregular black shapes (16) were obtained with permission from Chuah et al. (2004), which the authors had piloted for nameability. Shape and location stimuli are available in Appendix A.

Design and Procedure. Experiment 1 took the form of a 2 x 5 design. The task was carried out either in silence (the control condition) or under articulatory suppression (the suppression condition), a factor which was manipulated between-subjects. In addition, five probe conditions were manipulated (within-subjects), as outlined below.

The experiment began with a self-paced set of instructions informing participants that they would be presented with three shapes appearing sequentially in different locations, and that they would then be presented with a single probe shape in a location. The task was to press 'yes' if the probe represented *both* a shape and location that they had seen in the TBR array (irrespective of whether the features were initially presented as part of the same object), and 'no' if not. Additionally, participants taking part in the suppression condition were asked to repeat the words 'one – two' while shapes were appearing on-screen and during the retention interval.

The TBR array consisted of three sequentially presented black polygons (from a

possible set of 16) appearing in 3 irregularly distributed locations (from a possible set of 16) within a 160mm x 135mm black frame, against a white background. Each shape stimulus was filled in black, and contained within a 20mm x 20mm black border. The probe consisted of a single shape in a location, and could be one of five different types as listed below. The two positive probe types (requiring a 'yes' response) were as follows: *intact* probes comprised a shape in location, as seen in the TBR array on that trial; *re-paired* probes comprised a shape in a location originally occupied by another TBR shape on that trial. The three negative probes (requiring a 'no' response) were: *both-features-new* probes, comprising a new shape in a new location; *new-shape* (old location) probes, consisting of a location that was seen in the TBR array on that trial, occupied by a shape that was not seen; finally, *new-location* (old shape) probes, comprising a shape that was seen in the TBR array on that trial, occupying a location that was not seen on that trial. Participants were instructed to keep their fingers over the response keys, and to respond as quickly yet accurately as possible.

Figure 4 illustrates the time course of trials in Experiment 1A. Each trial began with an instruction to 'start repeating' appearing for 1000ms (replaced by a string of hashes in the control condition). This was followed by a 1000ms blank frame. The TBR items were then presented sequentially, each for 1500ms (at the offset of the preceding shape). Following a 2000ms retention interval, the probe item appeared on-screen until a yes/no response was collected. The next trial was initiated as soon as participants made a response to the probe via a key press on the keyboard, and following the presentation of a feedback display. The feedback display consisted of the response time achieved on the preceding trial and of average accuracy attained on the task so far (visible for 3000ms). Participants used their index fingers, and pressed the 'y' button to indicate a 'yes' response and the 'n' for a 'no' response.



Figure 4. Experiment 1A - The time course of trials, and respective trial types.

Trials were constructed by randomly assigning three shapes to locations, with the constraint that each shape/location feature occurred equally often, and was not repeated within a trial. Probes featuring an old (seen before) feature were sampled equally from serial positions one, two and three (i.e., not applicable to *both-features-new* probes). There were 21 trials for each probe type, resulting in 105 trials in total. Five practice trials were also included, but were not subjected to statistical analysis.

9.2. Results

9.2.1. Data Analysis

In the following analyses, data are presented in accordance with two indices of performance: reaction times (median 'RTs' for correct responses), and hits (accuracy, denoting the % of correct responses)¹. An alpha level of p = .05 was used for all experiments.

¹ Accuracy data were also analysed with d-prime (Macmillan & Creelman, 1991). However, both accuracy measures provided the same results. Details of how this paradigm can be analysed with the signal detection method are presented in Appendix B.

Analyses for Experiment 1A were broken down as follows: firstly the effect of concurrent articulation was assessed, by way of a 2 (quiet versus suppression) x 5 (probe type) ANOVA (Analysis 9.2.2). Guided by the results of the main ANOVA, subsequent tests assessed the binding effect by comparing the two positive probe types (Analysis 9.2.3); and finally, performance for the three negative probe conditions was compared (Analysis 9.2.4).

9.2.2. Articulatory Suppression and Task Performance

The following analysis compared probe performance under silent and articulatory suppression conditions. The analysis served to indicate whether shape/location stimuli were encoded visually/verbally, and further allowed establishment of whether subsequent analyses could be simplified by collapsing performance across the silent and suppression conditions.

Reaction Time. A 2 (quiet versus suppression) x 5 (probe type) ANOVA for repeated measures, with condition (quiet or suppression) as a between-subjects factor indicated a significant main effect of probe, F(4, 184) = 18.01, MSE = 15497.14, p < .001; no significant main effect of condition, F(1, 46) = .00, MSE = 240440.84, p = 1.00; and finally, no interaction between factors, F(4, 184) = 1.0, MSE = 15497.14, p = .40. For RT measures, articulatory suppression did not have any detrimental effect on probe performance, and did not interact with probe type.

		Quiet Condition				AS Condition			
		Accuracy (% Correct)		RT (Milliseconds)		Accuracy (% Correct)		RT (Milliseconds)	
Probe	n	М	SE	М	SE	М	SE	М	SE
Intact	24	75.4	2.72	948.06	61.48	74.61	2.20	940.19	41.20
Re-paired	24	73.42	2.53	997.10	59.25	74.81	2.74	972.4	38.13
Both-Features-New	24	91.35	2.18	844.9	51.06	86.31	2.74	875.42	39.32
New-Location	24	83.14	3.14	914.48	57.74	80.17	3.03	882.44	34.07
New-Shape	24	63.7	3.60	1008.48	49.15	51.83	3.50	1043.6	46.31

Table 1. Mean (M) accuracy scores, RT measures (median RTs for correct responses) and standard error (SE) values across probe type as a function of condition (quiet vs. suppression) in Experiment 1A.

Accuracy. A 2 (quiet versus suppression) x 5 (probe type) ANOVA for repeated measures computed for accuracy measures indicated a significant main effect of probe, F (4, 184) = 39.16, MSE = 239.08, p < .001; no significant main effect of suppression, F (1, 46) =

2.57, MSE = 341.77, p = .12, and no interaction between these factors, F(4, 184) = 1.87, MSE = 239.08, p = .12. Similar to the RT analysis, for accuracy measures articulatory suppression did not affect performance, and did not interact with probe type. Descriptive statistics for these analyses are presented in Table 1.

Summary. The requirement to articulate during the task did not have any detrimental effect on accuracy or RT performance, suggesting that participants did not recode the shapes verbally. This confirms that the selection of shapes by Chuah et al. (2004) was effective in ensuring stimuli were difficult to name. In order to analyse in more depth performance differences between the probe types, data were collapsed across the silent and suppression conditions in the subsequent analyses. As the comparison of intact and re-paired probe conditions was pivotal in establishing feature binding, and negative probe conditions largely served as filler trials, analyses decomposing the main effect of probe noted in analysis 9.2.2 were carried out separately for positive and negative probe conditions (Analyses 9.2.3 & 9.2.6, respectively).

9.2.3. Assessing the Binding Effect

Intact and re-paired probe performance measures (collapsed across the quiet and suppression conditions) were compared in order to ascertain whether there was evidence of binding in Experiment 1A.

Reaction Time. Positive probe RT measures were subjected to a one factor (positive probe) ANOVA for repeated measures, which indicated a significant binding effect, F(1, 47) = 10.62, *MSE* = 3730.45, p < .01, confirmed by effect size computations (Cohen's d)² to be small in magnitude, d = .17. The data are presented in Figure 5A.

Accuracy. A one factor (positive probe) ANOVA computed for accuracy measures indicated no significant binding effect, F(1, 47) < 1. The data are depicted in Figure 5B.

² Across experiments we report effect size computations using the Cohen's *d* coefficient. In order to account for within-subjects comparisons, we followed the recommendations of Dunlop, Cortina, Vaslow and Burke (1996) whereby the original standard deviations for each group mean were pooled to compute *d*.



Figure 5. Experiment 1A - The binding effect as denoted in Analysis 9.2.3. Panel A: A significant binding effect for median RT measures (p < .01). Panel B: No significant binding effect for accuracy measures (% correct; p > .05). Bars represent one standard error of the mean.

Summary. Analyses indicated a significant binding effect for RTs, but not for accuracy measures. There are however possible limitations to this interpretation. As stimuli were presented sequentially, the encoding and maintenance of TBR items may have been subject to processes inherent to the recognition of sequential stimuli (recency effects in particular). Consistent with this contention, evidence suggests that recognition performance for sequentially presented visual stimuli exhibits strong one-item recency effects (e.g., Hitch & Walker, 1991; Phillips & Christie, 1977a; b).

An important constraint on analysis is that intact and re-paired probes are not subject to serial positions effects in the same way. For example, intact probes comprise two features, each from the same serial position (i.e., both features from either serial position 1, 2 or 3), whereas re-paired probes comprise shape and location features from different serial positions, as illustrated in Figure 6.

When an intact probe represents features from serial position 3, it will necessarily have a recency advantage over re-paired probe features, which by their nature can never both occupy serial position 3. This recency advantage could account for the RT binding effect noted in Analysis 9.2.3.


Figure 6. Experiment 1A - Illustration of possible intact and re-paired probe feature serial position combinations. Dashed lines represent intact probes and solid lines represent re-paired probes.

It is important to ensure that the measure of binding is not confounded by recency effects. Analysis 9.2.4 was devised to check for recency effects for intact probes which may have confounded the binding effect noted for RT measures.

9.2.4. Serial Position Effects for Intact Probes

In the following analyses, the intact probe performance measures were broken down into serial positions. This analysis was devised in order to check whether a recency effect occurred in the intact probe condition.

Reaction Time. Intact probe serial position RT data were subjected to a one factor (serial position) ANOVA for repeated measures. The analysis indicated a significant main effect of serial position, F(2, 94) = 7.36, MSE = 20769.78, p < .01. LSD post-hoc tests indicated significantly faster responses when features were probed from serial position 3 relative to serial positions 1 and 2, ps < .01, but no significant difference between RT performance for serial positions 1 and 2, p > .05. The data therefore show a one-item recency effect in line with past studies of recognition performance for sequential visual stimuli (e.g., Hitch & Walker, 1991; Phillips & Christie, 1977a;b). The implication for the present study is that our measurement of the binding effect must be revised in order to discount the possibility that what appeared to be a binding effect in analysis 9.2.3 was not an artefact. The data are illustrated in Figure 7A.



Figure 7. Experiment 1A - Intact probe performance where both features (shape and location) were probed from serial positions 1, 2 and 3. Panel A: Intact probe serial position RT data, denoting a finalitem recency effect. Panel B: Intact probe serial position accuracy (% correct) data, further indicating a final-item recency effect. Bars represent one standard error of the mean.

Accuracy. Intact probe serial position accuracy data were subjected to a one factor ANOVA which similarly indicated a significant main effect of serial position, F(2, 94) = 15.73, MSE = 250.54, p < .001. LSD post-hoc tests indicated that accuracy for features probed from serial position 3 was significantly higher than where features were probed from serial positions 1 or 2, ps < .001. Further, performance where features were probed from serial position 1 was marginally better than where they were probed from serial position 2, p = .05, see Figure 7B.

Summary. For both dependent measures, analyses indicated a recency effect for intact probes. In order to provide a meaningful comparison between intact and re-paired probes, analysis 9.2.5 was devised to measure binding independently of this recency effect.

9.2.5 Assessment of the Binding Effect: Recency Equated

The following analysis was devised to remove any intact probe advantage pertaining to serial position 3. The analysis assessed binding at serial positions 1 and 2 only. To achieve this, performance for intact probes presented in serial positions 1 and 2 was averaged, and compared to averaged performance for re-paired probes made of features presented in serial positions 1 and 2.

Reaction Time. The recency controlled measures were subjected to a one factor (intact versus re-paired probe) ANOVA for repeated measures, which indicated a significant main effect of binding, F(1, 47) = 4.34, MSE = 17233.70, p < .05. When overshadowing serial position effects were removed, the binding effect remained for RT measures. As in Analysis 9.2.3, effect size computations (Cohen's *d*) indicated that the binding effect was small in magnitude, d = .22. The data are depicted in Figure 8A.



Figure 8. Experiment 1A - The binding effect when recency effects were controlled for. Panel A: A significant binding effect for RT measures (p < .05). Panel B: No significant binding effect for accuracy (% correct) measures (p > .05).

Accuracy. A one factor (intact versus re-paired probe) ANOVA computed for accuracy measures indicated no significant main effect of binding once recency was controlled for, F(1, 47) < 1. Accuracy data are presented in Figure 8B.

Summary. When overshadowing recency effects were removed, evidence for location binding was found for RT measures, but not for accuracy measures. The following analysis assessed performance for negative probe trials.

9.2.6. Assessment of Negative Probe Performance

The analyses above provided a direct evaluation of the binding effect by comparing the two critical probe types (intact and re-paired). While the negative probes fulfilled the role of filler trials, they also held potential information on binding in terms of whether shape and location features contributed equally to the recognition of bound representations. More specifically, comparison of performance in the both-features-new condition to the new-shape and new-location conditions would indicate which feature (shape or location) constituted the best indicator for rejecting foils. Negative probe performance is assessed below.

Reaction Time. Negative probe RT data were subjected to a one factor (negative probes) ANOVA for repeated measures. The analysis indicated a significant main effect of negative probe, F(2, 94) = 29.21, MSE = 14560.40, p < .001. LSD post-hoc tests indicated that RTs for both-features-new probes were significantly faster than for new-location and new-shape probes, ps < .05. Further, RTs for the new-location condition were significantly faster than those in the new-shape condition, p < .001. The data are presented in Figure 9A.

Effect size computations indicated that the difference in performance between the both-features-new and new-location conditions was small, d = .17; whereas the difference in performance between the both-features-new and new-shape conditions was medium, d = .73. The RT data therefore suggest unequal contributions of shape and location information, whereby the presentation of an old location delayed the participants' responses.

Accuracy. A one factor ANOVA on negative probe accuracy measures indicated a significant main effect of negative probe, F(2, 94) = 76.37, MSE = 243.37, p < .001. LSD post-hoc tests indicated that performance was significantly superior for both-features-new probes compared to new-shape and new-location probes, ps < .001. Furthermore, performance for new-location probes was significantly better than for new-shape probes, p < .001. Effect size analyses indicated the effect between both-features-new and new-location probes was medium, d = .53; whereas the difference between both-features-new and new-shape probes was very large, d = 2.02 (Figure 9B).



Figure 9. Experiment 1A - Negative probe performance denoting the relative ease with which participants rejected probes comprising a new location (both-features-new; and new-location probes) relative to a new shape (new-shape probes). Panel A: RT measures. Panel B: Accuracy measures (% correct). Bars represent one standard error of the mean.

Summary. The analysis of negative probes in Experiment 1A revealed asymmetrical contributions of shape and location to memory performance. More specifically, performance measures were comparatively poor for the new-shape (old location) condition relative to the new-location (old shape) condition, suggestive of a facilitating effect on performance of changing a spatial location, relative to changing the identity of a shape.

9.3. Discussion

Experiment 1A yielded three key findings. Firstly, Experiment 1A demonstrated location binding for visual and spatial features, even after possible confounding recency effects were removed. The present results therefore suggest that visual and spatial information may be bound in WM. A binding interpretation, rather than an independent storage one is appropriate as the featural demands of both intact and re-paired probes were the same. If features simply being stored independently, one would predict no performance difference between these two probe types. The data are consistent with those noted in property binding studies (e.g., Ceraso et al., 1998; Delvenne & Bruyer, 2004; Walker & Cuthbert, 1998) which all suggest that features are most likely to be integrated if they form properties of the same object. As spatial location necessarily constituted a property of the

shape stimuli, one may argue that the results pertain to property binding. Furthermore, with respect to the unitisation effect (e.g., Asch et al., 1960; Ceraso et al., 1998, Delvenne & Bruyer, 2004), the present results indicated that unitisation type effects occurred for our stimuli whether or not participants were precluded from verbally recoding through the use of an articulatory suppression task (as indicated by a lack of interaction between suppression and probe in Analysis 9.2.2). This suggests that the encoding strategy used in Experiment 1A did not take place through verbal labelling. Thus one may argue that, consistent with previous research (e.g., Luck & Vogel, 1997) verbal recoding is not a widely used strategy in this type of single probe paradigm. The intact/re-paired probe difference supports the hypotheses that either a) visual and spatial features are integrated into whole new objects to be stored in memory or b) that independently stored features are integrated by virtue of feature links which indicate which features belong together. Although the present experiment cannot distinguish between these two possibilities, analysis of negative probes was supportive of the latter, as discussed at the end of this section.

The second key finding was that the sequential presentation of items resulted in a one-item recency effect. This effect is consistent with much previous research. For example, McElree and Dosher (1989) observed that in serial presentation recognition paradigms, the item presented most recently is recognised at test with a sizeable advantage over earlier presented items, even with small set sizes (of 3-6 items). Additionally, evidence suggests pronounced recency effect pertaining to the final item presented in paradigms using sequentially presented visual stimuli (e.g., Hitch & Walker, 1991; Phillips & Christie, 1977a;b). It was noted that in terms of recency, intact probes may have had an advantage over repaired probes, the features of which could never both occupy serial position three. Once accounted for, however, the binding effect remained.

An alternative suggestion as to why there was a pronounced final-item recency effect may be that purely visual-spatial representations of stimuli are short-lived. In the original Prabhakaran et al. (2000) paradigm, bound letter and location features could persist for at least 5 seconds. The enduring binding effect noted for verbal-spatial stimuli may be due to letter stimuli being supported by pre-existing LTM representations, whereas in the present study, memory representations for shapes presumably were not supported in a similar way.

Consistent with the idea of a short-lived visual code is the work of Posner and Mitchell (1967), who demonstrated that subjects instructed to respond 'same' to two letters possessing the same name was faster when the letters were physically identical (e.g., E E) than when they were only acoustically similar (e.g., E e), although the visual over verbal advantage was only present for around 2 seconds. One important question pertaining to location binding is whether or not the maintenance in memory of bound versus separate stimuli is short-lived. From the present study it is not possible to make any assumptions about the decay rate of bound representations. This point will be addressed in Experiment 1B.

A further possible limitation to the paradigm used in Experiment 1A is that the sequential presentation of items may have resulted in interference between items, such that subsequently presented items may have interfered retroactively with previously presented items. Using a single probe change detection paradigm with sequentially presented items, Allen et al. (2006) demonstrated that binding may be particularly susceptible to the presentation of subsequent items, causing the links between features to dissolve. This may explain why binding was only noted for one dependent measure in Experiment 1A.

Finally, the pronounced recency effect for the last stimulus seen may have been caused by 'matching' processes. Consistent with this idea, Posner, Boies, Eichelman and Taylor (1969) noted that retrieval advantages for visually presented items could reflect low-level physical or visual matching. The implication of this for the present study is that the most recently presented item (or indeed, all items in subsequent experiments using a simultaneous presentation procedure) may simply have been 'matched' to the probe via this process (c.f., McElree & Dosher, 1989, who found strong final item recency effects when a visual mask was used, equivalent to that found when a mask was not used, although their stimuli consisted of digits). In order to remove this possibility, a visual mask was incorporated into Experiment 1B.

The final result deserving commentary arising from the analysis of negative probes in Experiment 1A was the evidence of an asymmetrical contribution of shape and location features to recognition. Specifically, performance in responding to new-shape (old location) probes was comparatively poor to performance in responding to new-location (old shape) probes. This finding suggests that changes in spatial location (where shape remained

consistent) may have been more salient than changes in shape (when location remained consistent). It should be noted however that location change was not the only contributor to performance, as performance in rejecting both-features-new probes was superior to that observed in the new-location condition. The finding deserves two theoretical considerations.

The first stems from the contributing processes in recognition of familiarity and recollection. The Dual-Process theory suggests that memory performance in recognition tasks is based on two independent processes – familiarity and recollection. The former is assumed to be fast and automatic, while the latter is comparatively slower and controlled. Familiarity is thought to be well described by signal detection theory (e.g., Yonelinas, 1994), whereby the variable strength of the familiarity of old and new items partially overlap. This overlap results in the selection of a familiarity level – a cut off point at which familiar and unfamiliar items are demarcated. Anything which falls above this level is judged to be old (i.e., highly familiar, and seen before), and anything that falls below is judged as new (i.e., not very familiar, and not seen before).

In terms of negative probe performance, superior recognition of both-features-new probes would be derived by the fact that both features form 'unfamiliar' cues, and thus are rejected with relative ease. As spatial location seemed to be the more salient feature, location change may have formed a good cue for response. Consistent with this interpretation, when a new-shape (old location) probe was encountered, poor performance may have arisen from conflict between the familiarity signal emanating from the seen-before location, and the highly unfamiliar shape feature. The familiarity of the location may have pushed participants to respond that they had seen both the shape and location before, a familiarity feeling which may have been difficult and time consuming to override (consistent with the RT data).

The second theoretical commentary is with regard to configural processing. Jiang et al. (2000) demonstrated that spatial working memory is based on configurations, and proposed that VSWM may be organised hierarchically. On encountering a visual image, a spatial configuration of items is automatically formed and the features comprising the configuration are bound to the respective parts of that configuration. Further, Olson and Marshuetz (2005) noted that visual items are encoded in terms of relative spatial location, and

demonstrated that a physical frame, other distracters, or a fixation cross can form good memory reference frames. In terms of the performance differences between new-location and new-shape probes, hierarchical processing may have played a role. For example, although a single probe was used, the frame within which the items were presented (the TBR array and the probe) may have served as a good frame of reference for locating the memory items. Thus, deriving a change in spatial location may have proved easier and faster than deriving a new shape within an already seen location since the analysis of the layout of the scene precedes the analysis of the composite items of that configuration (see Navon, 1977). Thus when the location was the same but the shape was different (new-shape probes) performance may have been hampered by this first stage of processing, which may in turn have pushed the participant towards an erroneous positive response before more fine grained analysis of the contents of that spatial location took place, accounting for the slower RTs for correct responses in the new-shape condition. In short, the finding suggests that visual and spatial features may contribute asymmetrically to feature integration. This issue will be more directly assessed in Series 2.

10. Experiment 1B

Although location binding was demonstrated in Experiment 1A, there were a number of methodological complications resulting from the sequential presentation of items. Firstly, analysis was complicated by recency effects (e.g., Hitch & Walker, 1991; Phillips & Christie, 1977a;b). As discussed, this recency effect may have stemmed from either a short-lived visual code (e.g., Posner & Mitchell, 1967), retro-active interference from subsequently presented items (e.g., Allen et al., 2006); or low level visual matching of the final item to the probe item (e.g., Posner et al., 1969).

The existence of a short-lived visual code speaks to one of the aims of the present thesis: what are the temporal dynamics of bound representations? In order to gain a better idea of whether bound representations are short lived, Experiment 1B included a variable lag interval between the TBR array and the probe (250ms, 500ms, 2000ms and 4000ms). In order to remove recency effects, in Experiment 1B, TBR items were presented simultaneously. Finally, in order to remove any effect of low-level visual matching which was a possible confound when items were presented sequentially, but could equally contribute to performance when items are presented simultaneously. Experiment 1B included a visual mask, presented for 150ms at the offset of the TBR array. This manipulation constituted an improvement on the methodology of Prabhakaran et al. (2000) who did not include this control in their original design.

As in Experiment 1A, the basic paradigm involved the presentation of an array of three shapes in locations, within a frame. The array was then followed by a visual mask, a variable lag interval, and finally a single probe item. Again, there were two critical probe types – *intact probes* (a shape in location as in the array) and *re-paired probes* (a shape in a location originally presented with another shape). Binding was measured as an intact over repaired probe processing advantage.

10.1. Method

Participants. Eighty undergraduate volunteers (40 in the control condition, and 40 in the articulatory suppression condition) participated in the one hour experiment for course credit, or for a small honorarium. All participants reported normal or corrected-to-normal

vision, and all were naïve to the aims of the experiment. Three participants were dropped from analyses for scoring well below chance on accuracy measures for one or more probe type (resulting in n = 40 in the control condition, and n = 37 in the suppression condition).

Materials. As in Experiment 1A.

Design and Procedure. Procedural details were as in Experiment 1A, unless otherwise stated. Experiment 1B took a 2 (quiet versus suppression) x 4 (lag interval) x 5 (probe type) design, with articulatory suppression as a between-subjects factor. The lag interval manipulation varied between 250ms, 500ms, 2000ms and 4000ms, and was blocked. Positive probe conditions (requiring a yes response) were *intact* and *re-paired* probes; and negative probes (requiring a no response) were *new-shape*, *new-location* and *both-features-new* probes (for full details, see the method section of Experiment 1A). The visual mask was composed of multiple oblong forms, filled in black, scattered across the array in different orientations.

Figure 10 illustrates the time course of all trials in Experiment 1B. Each trial began with a 'start repeating!' instruction appearing for 1000ms (replaced by a string of hashes in the control condition). This was followed by a blank frame which appeared for 1000ms. The TBR items were then displayed for 2000ms within the frame, followed by a mask which appeared on-screen for 150ms at the offset of the TBR array. Then there was a variable lag period of 250, 500, 2000 or 4000ms, presented in separate blocks of trials. The 150ms duration of the visual mask was included in the lag period. The probe item then appeared onscreen until participants made a yes/no response. The next trial was initiated when a response was collected, following the presentation of feedback (as in Experiment 1A). As the lag variable was blocked, the experiment was split into four sections, separated by an instruction screen whereby participants to take a short break.



Figure 10. Experiment 1B - The time course of the different types of trials in Experiment 1B.

Trials were constructed by randomly assigning three shapes to locations, with the constraint that each shape/location feature occurred equally often within each lag block, and was not repeated within a trial. The lag block order was balanced using a Latin square. There were a total of 80 trials for each of the four lag blocks (16 trials for each type of probe). The total number of trials was 320, plus 5 trials for practice which were not included in the statistical analyses.

10.2. Results

10.2.1. Data Analysis

As in Experiment 1A, RT and accuracy measures are presented separately. The first analysis (Analysis 10.2.2) examined whether suppression had an effect on probe performance in order to establish firstly whether verbal labels were employed, and secondly whether analyses pertaining to the binding effect (and negative probes) could be simplified by collapsing the two data sets. Subsequent analyses assessed the binding effect (Analysis 10.2.3), and negative probe performance (Analysis 10.2.4).

10.2.2. Articulatory Suppression and Task Performance

The present analysis assumed a 2 (quiet versus suppression) x 4 (lag) x 5 (probe type) design, and assessed whether verbal labelling contributed to performance on the probe task. Full descriptive statistics for the results of Analysis 10.2.2 are available in Appendix C.

Reaction Time. Reaction time measures were subjected to a 2 (quiet versus suppression) x 4 (lag) x 5 (probe type) ANOVA for repeated measures, with suppression as a between-subjects factor. The analysis indicated a significant main effect of suppression, *F* (1, 75) = 8.07, *MSE* = 683198.96, p < .001, whereby RTs were faster in the quiet condition (*M* = 771.70, *SE* = 29.22) relative to the suppression condition (*M* = 911.84, *SE* = 30.39). Additionally, there was a significant main effect of probe, *F* (4, 300) = 78.93, *MSE* = 25276.40, p < .001; and a significant main effect of lag, *F* (3, 225) = 3.29, *MSE* = 73261.80, p < .05. Trend analyses were carried out in order to assess the pattern of performance over the lag intervals. Trends assessed were linear, quadratic and cubic. Only significant trends in the lag data, *F* (1, 75) = 8.07, *MSE* = 65537.73, p < .01, described by a general decline in RT performance, as lag increased.

There was no interaction between lag and condition, F(3, 225) = .39, MSE = 73261.80, p > .05; no interaction between probe and condition, F(4, 300) = .33, MSE = 25276.40, p = .86; no three-way interaction between factors, F(12, 900) = 1.33, p = .20. Finally, there was a significant interaction between lag and probe, F(12, 900) = 4.87, MSE = 12648.65, p < .001. In sum, the requirement to articulate during the probe task led to a slowing of RTs. However, the effect was non-specific, as indicated by a lack of interaction between probe type and articulation. The results additionally suggested a significant interaction between lag and probe, in subsequent analysis sections assessing positive and negative probe performance individually.

Accuracy. A 2 (quiet versus suppression) x 4 (lag) x 5 (probe type) ANOVA for repeated measures with suppression as a between-subjects factor indicated no significant main effect of condition, F(1, 75) = 2.01, MSE = 1122.74, p = .16; a significant main effect of

probe, F(4, 300) = 92.54, MSE = 643.19, p < .001; and a significant main effect of lag, F(3, 225) = 17.50, MSE = 126.51, p < .001, characterised by a significant linear trend, F(1, 75) = 45.44, MSE = 118.21, p < .001, a significant quadratic trend, F(1, 75) = 4.52, MSE = 141.13, p < .05, and a significant cubic trend, F(1, 75) = 5.26, MSE = 120.17, p < .05.

There was no interaction between lag and condition, F(3, 225) < 1; no interaction between probe and condition, F(4, 300) = 1.92, MSE = 643.19, p = .11; a significant interaction between lag and probe, F(12, 900) = 11.83, MSE = 190.08, p < .001; and finally, no three-way interaction between factors, F(12, 900) < 1. In sum, accuracy data indicated that performance on the probe task was not adversely affected by the suppression of articulation. The interaction between lag and probe will be decomposed in subsequent analysis sections assessing positive and negative probe performance, respectively.

Summary. The results indicated that suppression did not have an effect on probe performance above that of a general slowing effect for RT measures. As suppression had no effect on accuracy measures, and only yielded a general slowing effect for RT measures, the data set was collapsed across conditions. All subsequent analyses were carried out on this collapsed data set. In order to establish the cause of the main effect of probe noted in both dependent measures, and, more specifically, to assess whether there was any evidence for binding, analyses were decomposed so that positive and negative probe performance were analysed separately. The significant interaction between lag and probe, noted for both dependent measures was assessed in more detail through these separate positive and negative probe analyses.

10.2.3. Assessing the Binding Effect

The following analysis took the form of a 4 (lag) x 2 (intact versus re-paired probe) design, and assessed whether there was any evidence for binding in Experiment 1B.

Reaction Time. Median RTs for correct responses for intact and re-paired probes are presented as a function of lag in Figure 11A. The data were subjected to a 4 (lag) x 2 (intact vs. re-paired probe) ANOVA for repeated measures. The analysis revealed a significant main

effect of binding, F(1, 76) = 32.01, MSE = 8998.50, p < .001, confirmed by effect size computations (Cohen's *d*) to be small in magnitude, d = .02. Additionally, there was a significant main effect of lag, F(3, 228) = 9.57, MSE = 34144.20, p < .001; but no interaction between these factors, F(3, 228) < 1. Trend analyses indicated a significant linear trend, F(1, 76) = 21.72, MSE = 40880.83, p < .001, suggesting a linear increase in response time, as lag increased. In sum, RT measures indicated a significant binding effect which did not vary as a function of lag.



Figure 11. Experiment 1B - The binding effect as a function of lag in. Panel A: Significant main effects of binding and lag (ps < .05), but no interaction between factors (p > .05), for median RT measures. Panel B: Significant main effects of binding and lag (ps < .05) but no interaction between factors (p > .05) for accuracy measures (% correct). Bars represent one standard error of the mean.

Accuracy. Positive probe accuracy measures were subjected to a 4 (lag) x 2 (intact vs. re-paired probe) ANOVA for repeated measures which indicated a significant main effect of binding, F(1, 76) = 39.95, MSE = 172.92, p < .001; a significant main effect of lag, F(3, 228) = 37.51, MSE = 203.02, p < .001, characterised by a significant linear trend, F(1, 76) = 83.15, MSE = 245.32, p < .001; a significant quadratic trend, F(1, 76) = 4.63, MSE = 165.81, p < .05, and a significant cubic trend, F(1, 76) = 8.48, MSE = 197.94, p < .001; and finally, no interaction between factors, F(3, 228) = 1.80, MSE = 138.44, p = .15. Positive probe accuracy measures as a function of lag are presented in Figure 11B. Effect size computations

(Cohen's d) indicated the binding effect was medium in magnitude, d = .53.

In terms of the significant trends in the lag data, the linear trend denoted a general tendency for accuracy to decline as lag increased. The quadratic trend could be accounted for by the small increase in accuracy between the 250ms and 500ms lag intervals (for re-paired probes), while the cubic trend appears to account for both the improvement in performance between the two shorter lag intervals, and a levelling off of performance between the 2000ms and 4000ms intervals.

Summary. The results of Experiment 1B demonstrated robust binding effects for both dependent measures, which were not modified by variations in lag interval. Additionally, accuracy measures pertaining to the lag data indicated, in addition to a significant linear decline in performance, significant cubic and quadratic trends. The likely causal factor of this pattern of results was the increase in accuracy (for re-paired probes) between the 250ms and 500ms lag intervals.

10.2.4. Assessing Negative Probe Performance

An analysis of negative probe performance in Experiment 1A demonstrated unequal contributions of shape and location features to recognition memory. The following analysis assessed whether similar evidence was present in Experiment 1B.

Reaction Times. Figure 12A illustrates negative probe RTs as a function of lag. The data were subjected to a 4 (lag) x 3 (negative probe) ANOVA for repeated measures. The analysis indicated no significant main effect of lag, *F* (3, 228) = .62, *MSE* = 42436.76, *p* = .6; a significant main effect of negative probe, *F* (2, 152) = 99.01, *MSE* = 33998.37, *p* < .001, and finally, no interaction between factors, *F* (6, 456) = 1.61, *MSE* = 16736.61, *p* = .17.

LSD post-hoc tests on the main effect of negative probe indicated that RTs were significantly fastest for both-features-new probes relative to new-shape and new-location probes, ps < .001. Finally, RTs to new-location probes were significantly faster than to new-shape probes, p < .001.

Effect size computations indicated that the difference in performance between the

both-features-new and new-location conditions was small (d = .18), whereas the difference in performance between both-features-new and new-shape conditions was large (d = .79). The RT data therefore replicate the findings of in Experiment 1A.

Accuracy. Accuracy data for negative probes were subjected to a 4 (lag) x 3 (negative probe) ANOVA for repeated measures, which indicated no significant main effect of lag, F (3, 228) = 1.59, MSE = 124.10, p = .19; a significant main effect of negative probe, F (2, 152) = 128.07, MSE = 662.02, p < .001, and finally a significant interaction between negative probe and lag, F (6, 456) = 2.51, MSE = 129.53, p < .05. The data are illustrated in Figure 12B.

LSD post-hoc tests on the main effect of negative probe indicated that accuracy was significantly better for both-features-new probes relative to new-location and new-shape probes, ps < .001; and that accuracy for new-location probes was significantly better than for new-shape probes, p < .001, a pattern reflecting the RT analysis. Effect size computations suggested that for accuracy measures, the difference in performance between the both-features-new and new-location conditions was large (d = .88), whereas the difference in performance between both-features-new and new-shape conditions was very large (d = 2.32).

Planned comparisons assessing the interaction between negative probe and lag indicated no significant main effect of lag for both-features-new probes, F (3, 228) < 1; no significant main effect of lag on new-shape probes, F (3, 228) < 1; however, there was a significant main effect of lag on new-location probes, F (3, 228) = 6.36, MSE = 106.53, p < .001. The effect of lag was characterised by a significant linear trend, F (1, 76) = 11.72, MSE = 140.11, p < .01, whereby accuracy linearly increased as lag increased for this probe type. The interaction between lag and negative probe therefore was an artefact of the isolated effect of lag on new-location probes.



Figure 12. Experiment 1B - Negative probe performance demonstrating the facilitating effect on performance induced by a change in location (new-location probes), versus a change in shape (new-shape probes); along with the additive effect of changing both features (both-features-new probes). Panel A: RT measures; Panel B: Accuracy measures (% correct). Bars represent one standard error of the mean.

Summary. In terms of negative probe performance, the results mirror those of Experiment 1A. Specifically, the pattern of results in Experiment 1B was such that performance in responding to new-shape probes was relatively poor compared to responding to new-location probes, while the latter was closer (although still significantly different from) performance for both-features-new probes. This finding was reflected in effect size computations, which indicated a larger effect between both-features-new probes and new-shape probes; compared to the difference between both-features-new probes and new location probes.

10.3. Discussion

Experiment 1B yielded six key findings. The first finding of interest was that articulatory suppression did not affect performance (other than by slowing responses overall), indicating that the task tapped visuo-spatial memory processes rather than verbal processing. This is consistent with both the findings in Experiment 1A, and further data (e.g., Luck & Vogel, 1997) indicating that the attribution of verbal labels to stimuli is not a common strategy,

at least in recognition experiments.

The second key finding was the clear evidence for the integration of visual and spatial features. Even though the featural demands of both intact and re-paired probes were equivalent (i.e., both contained a shape and location attribute presented in the TBR array), recognition performance for intact probes was superior to that for re-paired probes, exhibiting a binding effect for both dependent measures. This binding effect may originate from the need for participants to decompose their memory representation in order to judge the presence or absence of both features for re-paired probes. As in Experiment 1A (although through using a simultaneous presentation procedure, and a more stringent method i.e., a visual mask), the results are consistent with those suggesting that binding is mediated by the way perceptual mechanisms perceive visual input (e.g., Delvenne & Bruyer, 2004; Xu, 2002a; Walker & Cuthbert, 1998) as only intact probe features, while appearing onscreen with other features, appeared as part of the same object in the TBR array.

The third key finding was that intact probe performance was consistently superior to re-paired performance at each lag interval. In the introduction to this experiment, it was speculated that binding between shape and location features may be a dynamic process. The binding between our features was present even at the shortest lag interval of 250ms, and remained for at least 4000ms (the longest lag interval included in this experiment; although one must factor in the fact that the TBR array was present onscreen for 2 seconds, potentially increasing the amount of time during which the bindings were formed). This finding suggests that bindings emerge relatively early, and can be maintained for a minimum of four seconds, demonstrating the robustness of the bound representation. The result is consistent, in terms of duration, with those noted in the perceptual binding literature (e.g., Hommel, 2002; Noles et al., 2005).

Similarly to Experiment 1A, the nature of the binding between shapes and locations could not be fully established from the results of Experiment 1B. Both full integration of features into a new object representation, and integration via connective links between features predict a decrement in performance in the re-paired condition relative to the intact condition, yet like Experiment 1A, negative probe performance suggested that shapes and locations may contribute asymmetrically to performance. A change in location (while shape

remained consistent) had a markedly larger facilitating effect on performance than a change in shape (while location remained consistent); a pattern reflected by both latency and accuracy measures. These results constitute a replication of the effect noted in Experiment 1A, with the further addition of the effect withstanding variations in lag interval. As previously discussed in the context of Experiment 1A, the finding may indicate that changes in location were more salient than changes in shape, an effect which could be attributable to the differential familiarity signals emanating from the shape and location features (e.g., Yonelinas, 1994); or by the necessity for an additional step in encoding constituent parts of a relatively automatically formed configuration of items (e.g., Jiang et al., 2000). The difference in performance between the both-features-new and new-location conditions was still significant however, indicating an additive effect of changing both features as opposed to simply changing item location.

The fifth point of interest in the analysis of accuracy for positive probes was the indication of quadratic and cubic trends in the lag data. While the overall pattern of performance for intact and re-paired probes was described by a linear decline in accuracy as lag increased, accuracy improved from the 250ms to the 500ms lag interval. This improvement in performance at such early stages of processing may be indicative of a consolidation period. Across a series of experiments, Jolicoeur and Dell'Acqua (1998) demonstrated that central attentional mechanisms are involved in the consolidation of visually presented stimuli into short-term memory. In their tasks, two concurrent tasks were performed. One involved the simple retention of visual stimuli, and the other, a speeded response to an auditory signal, presented at various points in time following the offset of the TBR visual material (stimulus offset asynchronies, or SOAs). Their key finding was that response times to the tone were slower at short SOAs, and decreased at longer SOAs, presumably once TBR information had been consolidated. The delay in responding to the tone was interpreted as the sign that the TBR visual stimuli were still being consolidated, a conclusion supported by the finding that this effect increased with the TBR workload. Consistent with this idea is a recent investigation by Jiang (2004) who found that there existed a consolidation period for a visual array of about of 200-500ms post stimulus offset. Thus, the performance difference between the 250ms and 500ms lag is consistent with independent

evidence for a consolidation process of visual stimuli.

The final finding of interest deserving commentary was with regard to the interaction between probe type and lag noted in the overall analysis (Analysis 10.2.2). Decomposition of analyses into positive and negative probe types suggested that positive probe performance was subject to performance decline as lag increased, whereas negative probe performance was not so characterised. The finding suggests that probe rejection/acceptance processes differ, and reinforces the appropriateness of analysing positive and negative probe conditions separately.

11. Series Discussion

11.1. Summary of Findings

The first aim of Series 1 was to demonstrate location binding, through an adaptation of the Prabhakaran et al. (2000) methodology. Across two experiments, location binding was demonstrated both when TBR items were presented sequentially (Experiment 1A) and simultaneously (Experiment 1B). In both experiments, participants had the task of reporting whether a single probe item represented both a shape and location seen in the TBR array. It was hypothesised that binding would be reflected by differential performance to two critical probe types, both requiring a 'yes' response. Intact probes consisted of a shape and location as seen in the TBR array, whereas re-paired probes consisted of a shape that was seen, and a location that was seen, but were not seen together (e.g., a shape swapped places with another shape from the array). In both Experiments 1A and 1B therefore, both shape and location features were task-relevant. Under these conditions, binding, indicated by an intact over re-paired probe processing advantage, was noted for RT measures in Experiment 1A where items were presented sequentially, and for both RT and accuracy measures in Experiment 1B where TBR items were presented simultaneously. The data are consistent with binding rather than independent storage as the latter would predict no processing difference between these two probe types.

The second aim of Series 1 was to ascertain a measure of the temporal dynamics of location binding, through the inclusion of a variable lag interval between presentation of the TBR array, and the probe (Experiment 1B). Results suggested that binding emerged relatively early (within 250ms post stimulus offset), and could be maintained for at least four seconds. The experiment constituted the first systematic assessment of the temporal dynamics of location binding in VSWM using this paradigm, but was consistent with findings in the perceptual binding literature (e.g., Hommel, 2002; Noles et al., 2005).

11.2. The Location Binding Effect in Context

Empirical investigation into binding within VSWM has indicated that visuo-spatial features may be 'chunked' together, providing economy of storage in terms of capacity within the cognitive system (e.g., Luck & Vogel, 1997; Wheeler & Treisman, 2002). The binding

benefit is limited to certain circumstances, however. For example, Olson and Jiang (2002) asserted that the binding that takes place in VSWM is weak, such that the capacity limitations imposed reflect the degree to which features are perceived as part of the same object, and even then, the benefit is not such that it 'doubles' available capacity for distinct features (c.f., Luck & Vogel, 1997).

Consistent with this view, much empirical research has supported the idea that perceptual 'object-hood' is a necessary condition for visuo-spatial binding in memory (e.g., Ceraso et al., 1998; Walker & Cuthbert, 1998; Xu, 2002a). More specifically, research has supported a distinction between property binding and part binding. Recall that 'property binding' refers to where features to be integrated are properties of an object, for example, the colour of an oriented line; whereas 'part-binding' refers to where features to be integrated on top of a square to form the percept of a house. A clear demonstration of this distinction was made by Xu (2002a), who established that two features were best encoded when they were from the same part (and thus properties of that part) of an object, and less well when there were from different parts of an object (see also Walker & Cuthbert, 1998; Delvenne & Bruyer, 2004).

The present experiments investigated binding between visual (shape) and spatial (location) attributes, the binding of which may necessarily constitute property binding, because spatial location is always a property of any visual feature. Results across two experiments demonstrated binding effects for these stimuli; in line with the property binding literature suggesting that binding is mediated by the way perceptual mechanisms process visual input (e.g., Delvenne & Bruyer. 2004; Xu, 2002a, Walker & Cuthbert, 1998). This was particularly the case in Experiment 1B where TBR items were presented simultaneously. Thus, on any given trial, there were six distinguishable task-relevant features present in the TBR array for encoding. That these features were 'bound' rather than stored independently was evidenced through a processing advantage of a probe representing an object from the TBR array, relative to a probe representing two features (visual and spatial) that did not form part of the same object in the TBR array.

Findings are also consistent with those suggesting a unitisation effect for purely visual stimuli (e.g., Asch et al., 1960; Ceraso et al., 1998; Delvenne & Bruyer, 2004). According to

Asch et al. (1960), unitisation occurs as a result of direct links formed between features perceived as belonging to the same object, which result in spreading activation between a cued feature and linked features. Thus retrieval of one feature results in the retrieval of all linked features. Further experimentation has found that this unitisation benefit is most pronounced under circumstances where participants are precluded from attributing verbal labels to visual stimuli, since verbal recoding is able to support associations across objects (Walker & Cuthbert, 1998).

Series 1, therefore, met the first objective of this thesis: firstly, location binding was demonstrated using a variation on the Prabhakaran et al. (2000) paradigm, and further the utility of using this paradigm for the investigation of location binding was established across two experiments.

A further theoretical aim was to try to ascertain the temporal dynamics of location binding, and gain a picture of whether location binding is a dynamic process, which could be either short-lived, or take time to develop (or indeed both). To achieve this, a variable lag interval was included between the TBR array and the probe in Experiment 1B. The lag was of 250ms, 500ms, 2000ms or 4000ms. It was hypothesised that if location bindings were short lived, binding effects would be present at the shorter but not longer lag intervals; conversely, if location bindings took time to emerge, binding effects would be present at the longer lag intervals and not the shorter lag intervals, for example.

The results indicated that the location binding effect was present from the shortest lag interval (250ms stimulus offset) through to the longest lag interval (4000ms stimulus offset) suggesting that location bindings emerged early, and could be maintained for at least 4 seconds after the disappearance of the TBR array. As previously noted, this experiment constituted the first empirical investigation of the temporal dynamics of location binding in the memory domain, but similar results pertaining to the durability of bound representations can be found in the perception literature. According to Noles et al. (2005), object-files can persist for up to 8 seconds. More relevantly, Hommel (2002) found evidence that integration in terms of his event-file formulation could be maintained for a minimum of 4 seconds, even in the absence of bottom-up input from the object, suggesting that event-files, and binding in memory may be synonymous in terms of durability (although they may differ in terms of internt

and strategy). That binding emerged quickly, and was not subject to decay over the retention interval, may be indicative of the fact that location binding is a relatively automatic process; however, there are limitations to this interpretation, which are discussed later.

The final discussion point arising from Series 1 was the finding of an asymmetry in the encoding of shape and location features. Two types of visuo-spatial feature binding have already been distinguished, namely part binding and property binding (e.g., Delvenne & Bruyer, 2004; Xu, 2002a). It was speculated in the introduction that location binding may represent a further distinguishable type of binding. This observation was made through evidence suggesting that the visual identity of object features is often accompanied by the encoding of spatial location, whether relevant for the completion of the task or not (e.g., Jiang et al., 2000; Olson & Marshuetz, 2005). Further, analogous effects pertaining to the automatic encoding of spatial location were noted in the attentional selection literature and the perceptual binding literature. On the former, evidence suggested that spatial attention is deployed even when irrelevant for the completion of attentional tasks (e.g., Lamy & Tsal, 2000; Hoffman & Nelson, 1981; Kim & Cave, 1995); that errors in tasks tapping selection for features other than spatial location are often spatial in nature (e.g., Tsal & Lamy, 2000), suggesting that the allocation of spatial attention may be necessary for the selection of object features. Additionally, in investigations of perceptual binding, evidence indicates that spatial information may be critical in the formation of object-files (e.g., Kahneman et al., 1992); and event files (e.g., Hommel, 2002), and one influential model of perceptual integration (FIT: Treisman & Gelade, 1980; Treisman, 1998) proposes that spatial attention may be the 'glue' that holds bound representations together.

In the context of Series 1, the binding effect itself is not telling on the asymmetry issue. While demonstrating compelling evidence for location binding, the results did not allow establishment of whether the binding of shape and location features results in the creation of a new object representation in memory, or whether location binding is better characterised by links between features which are stored independently. Both suppositions require that in order to find a memory match for re-paired probes, some decomposition of the bound memory representation must take place. In the case of the 'object' hypothesis, the memory representations would need to be decomposed into the constituent elements in order to find a

match for re-paired probes. Similarly, for the parallel storage hypothesis (Wheeler & Treisman, 2002), the link between the two features (shape and location) would need to be severed in order to respond to re-paired probes. However, results from the analysis of negative probes in both experiments indicate that the parallel storage account may be favourable over the 'object' account. Across both Experiments 1A and 1B, performance in responding to new-shape probes was comparatively poor relative to responding to new-location probes. This finding suggests that changes in location (while shape remained consistent) may have been more salient (and thus easier to spot) than changes in shape (while location remained consistent). Although it was established that location change was not the only contributing factor to performance (i.e., performance for both-features-new probes was superior to new-location probes), effect size computations assessing the magnitude of difference between the negative probe types indicated that performance on the new-location condition was closer to that on the both-feature-new condition than was performance on the new-shape condition.

Two theoretical considerations of this finding were made. Firstly, that the familiarity signals emanating from shape and location features may differ in strength (perhaps an artefact of stimulus saliency), contributing unequally to the response decision. More specifically, the weight of the signal from the location features appeared more likely to drive a participant to respond that they had seen both features before, than a shape feature did. The second consideration was with regard to configural hierarchical processing (e.g., Jiang et al., 2000), and in terms of the special status of location information in visual cognition (e.g., Hasher & Zacks, 1979).

In summary, the data reported above suggest that visual and spatial features can be bound in memory, providing evidence for location binding. Further the lag data suggest that visuo-spatial binding may be automatic, while the negative probe analyses suggest that it may be asymmetric. There are however possible limitations to these suggestions. With regard to the automaticity of binding, the nature of the task may be pivotal: although participants were not specifically instructed to bind the shapes and locations, they may have chosen to do so as a systematic strategy. In such case, the effect of binding observed may not be entirely automatic. With regard to the issue of asymmetry, it is important to assess to what extent this

finding follows from the use of a task in which both features were relevant. Hommel and Colzato (2004) found evidence to the effect that feature integration occurs if the task varies on a dimension which is relevant for the completion of the task, or it may occur if a feature is task-irrelevant, yet sufficiently salient. These issues were addressed in Series 2, which differed from Series 1 in that it required participants to attend to one feature only (either the shapes or the locations).

SERIES 2: LOCATION BINDING: ASYMMETRICAL FEATURE LINKS?

12. Series Introduction

Series 1 clearly demonstrated location binding for visuo-spatial stimuli using the Prabhakaran et al. (2000) paradigm. Additionally, negative probe performance suggested an asymmetry in the encoding of shape and location features. Series 2 assessed in more detail whether location binding is characterised by the creation of an entirely new object representation, or rather, whether it is better described by asymmetrical links between features. Specifically, the Series addressed two questions. Firstly, what are the products of location binding: whole new objects or asymmetric links between features? Secondly, is location binding automatic or mediated by task goals? The literature suggests that the encoding of visual identity appears to be obligatorily accompanied by the encoding of spatial location, whether or not relevant for the completion of the task (e.g., Jiang et al., 2000; Olson & Marshuetz, 2005). In contrast, the encoding of spatial location can be carried out in isolation of the visual features within those locations. Similar findings suggestive of the necessity of encoding spatial location in encoding visual features have been noted in the fields of visual selective attention (e.g., Hoffman & Nelson, 1981; Kim & Cave, 2001; Lamy & Tsal, 2000; Lamy & Tsal, 2001) and perceptual integration (e.g., FIT: Treisman & Gelade, 1980).

The asymmetry notion stands in contrast to typical formulations of feature integration, where the encoding of feature A is accompanied by the encoding of feature B and vice versa. Thus retrieval of one feature results in retrieval of all features. In Series 1, robust binding effects were noted; however it was not possible to ascertain the respective contributions of visual and spatial features to binding because both features were relevant for task completion (although negative probe performance was suggestive of unequal contributions). Series 2 differed from Series 1 in the extent to which each feature (shape and location) was (or not) task-relevant.

The second, related issue, addressed by Series 2 was whether visual and spatial features are integrated as a function of task goals, or whether they are integrated

automatically. For example, Hommel and Colzato (2004) found evidence that feature integration occurred for task-relevant features, or if one feature was task-irrelevant but sufficiently salient. Their experiment, however, investigated perceptual binding rather than location binding in memory.

Using the same procedure as in Experiment 1B, participants in Experiment 2A were instructed to attend to and remember shapes only, while ignoring locations. Conversely, in Experiment 2B participants were required to attend to and remember the locations only while ignoring the shapes. As in Series 1, binding was defined as an intact over re-paired probe performance advantage.

The experiment tested three hypotheses with regard to the nature of location binding. The *task-relevance* hypothesis states that the binding in memory takes place only when features to be encoded are both relevant for task completion. Consequently, integration may be dictated by what Hommel and Colzato (2004) referred to as 'participants attentional set'. In short, the hypothesis suggests that feature relevance dictates binding in memory, which may only take place as a function of task goals. A key prediction of the task-relevance hypothesis is that contrary to results found in Series 1, there should be no binding effect in either part A or B of Experiment 2, in both of which only one of the two features was attended.

The *automatic-binding* hypothesis suggests that binding between shape and location features takes place automatically. More specifically, the hypothesis suggests that upon encountering a visual array, the integration of object features occurs regardless of task goals. The idea in line with the supposition that the integration of visuo-spatial features results in the representation of an entire new object in memory, similar to that of the unitisation effect (e.g., Asch et al., 1960), where the integration of one feature is automatically accompanied by other features reciprocally. The automatic-binding hypothesis predicts binding effects in both parts A and B of Experiment 2. Finally, related to the automatic-binding hypothesis, the *asymmetry* hypothesis suggests that the encoding of spatial location is necessary for encoding object identity, whereas the encoding of spatial location is not obligatory for the encoding of object identity, consistent with other research into binding in memory (e.g., Jiang et al., 2000; Olson & Marshuetz, 2005). Therefore, binding to location occurs automatically when shapes only are attended, but not when locations are attended. The asymmetry hypothesis is consistent

with the supposition that visuo-spatial features in memory are bound by virtue of linkages formed between features that are stored in parallel (rather than the creation of an entirely new object), and that additionally the links created are asymmetrical in nature. Thus, feature A may be linked to feature B, while reciprocal links in the other direction are not realised. The asymmetry hypothesis predicts binding effects in Experiment 2A, but not in Experiment 2B.

13. Experiment 2A

In Experiment 2A, participants were instructed to focus on shapes only, and to ignore locations. The task was to press 'yes' if the probe represented a shape from the TBR array, and 'no' if it did not. Consistent with the use of the paradigm in Series 1, the critical comparison in Experiment 2A was between intact and re-paired probes. An advantage of the former over the latter would suggest that binding occurs automatically and is not necessarily mediated by intention to bind or task goals (i.e., the automatic-binding hypothesis). Alternatively, regarding the hypothesized asymmetry in contribution to binding of visual and spatial features, the encoding of the visual identity of items should automatically carry with it information about the spatial location of those objects, also predicting a binding effect (i.e., the asymmetry hypothesis). Both hypotheses make the same predictions with regard to binding in Experiment 2A, but differ in their predictions for Experiment 2B. Indeed, the automaticbinding hypothesis predicts binding effects in both part A and B of Experiment 2, whereas the asymmetry hypothesis predicts binding effects only in part A of Experiment 2. Finally, if no evidence for binding is noted in Experiment 2A, the results would be more consistent with the idea that binding does not occur automatically (when shape features only are task-relevant) and that two features must be task-relevant to foster binding (i.e., the task-relevance hypothesis).

13.1. Method

Participants. Twenty undergraduate volunteers participated in the one hour experiment for course credit, or for a small honorarium. All participants reported normal or corrected-to-normal vision, and all were naïve to the aims of the experiment.

Materials. As in Experiment 1B.

Design and Procedure. Stimuli, trial construction and trial events were as in Experiment 1B unless otherwise stated. Experiment 2A did not include a suppression condition as Series 1 clearly ruled out verbal recoding as a mediator of performance on this task and for these stimuli. Participants were instructed that the task was to press 'yes' if the

probe represented a shape that they had seen before in the TBR array, and to press 'no' if it did not. They were further instructed to ignore the locations of the shapes, since they were irrelevant for task completion. Due to the demands of the experiment, the positive to negative probe frequency ratio was 3:2. The three positive probe conditions (requiring a 'yes' response by virtue of containing a seen-before shape) were *intact* probes, *re-paired* probes and *new-location* probes. The two negative probe conditions were *both-features-new* probes and *new-shape* probes.

In order to keep procedures consistent across experiments, the instruction to start repeating that was used in Experiment 1B was replaced with a string of hashes, analogous to what participants saw in the control condition of Experiment 1B.

13.2 Results

13.2.1. Data Analysis

In the following analyses, both accuracy (% correct) and RT measures are presented. For each measure, a first analysis assessed intact and re-paired probe performance, in order to establish if there was any evidence for binding when shapes only were task-relevant (Analysis 13.2.2). Due to the demands of the experiment, new-location probes also constituted a positive probe condition (i.e., comprised a shape seen before in the TBR array, occupying a location that was not seen). However, as the new-location condition served as a filler condition in this context, and was not of theoretical interest with regard to binding, results pertaining to the new-location condition are not presented in the analysis of binding. Analyses including all three positive probe conditions can however be found in Appendix D. The final analysis assessed negative probe performance (Analysis 13.2.3), as performance differences between both-features-new and new-shape probes was thought to be potentially informative on the issue of which features were subject to encoding in this task. Descriptive statistics for all analyses in Experiment 2A are presented in Appendix E.

13.2.2. Assessing the Binding Effect

Reaction Time. Reaction time data for the intact and re-paired probe conditions were subjected to a 4 (lag) x 2 (intact vs. re-paired probe) ANOVA for repeated measures. The

analysis indicated a significant main effect of lag, F(3, 57) = 10.72, MSE = 22101.65, p < .01, characterised by a significant linear trend, F(1, 19) = .13.66, MSE = 23811.86, p = .002, and a significant quadratic trend, F(1, 19) = 10.58, MSE = 13083.35, p < .01. There was a significant binding effect, F(1, 19) = 9.17, MSE = 6733.04, p < .01, and finally no interaction between factors, F(3, 57) < 1. The binding effect, as a function of lag is presented in Figure 13A. Effect size computations (Cohen's *d*) indicated that the binding effect was small in magnitude, d = .27.



Figure 13. Experiment 2A – Binding as a function of lag. Panel A: A significant binding effect (p < .05), a significant main effect of lag (p < .05), and no interaction between factors (p > .05) for RT measures. Panel B: A marginally significant binding effect (p = .06), a significant main effect of lag (p < .05), and a significant interaction between factors (p < .05) for accuracy measures (% correct). Bars represent one standard error of the mean.

In sum, when shapes were task-relevant, there was a significant binding effect across all four lag intervals. Additionally, the analysis of the lag data indicated a significant quadratic trend, suggestive of an improvement in performance between the 250ms and 500ms lag intervals.

Accuracy. A 4 (lag) x 2 (intact vs. re-paired probe) ANOVA for repeated measures on accuracy data indicated a significant main effect of lag, F(3, 57) = 14.30, MSE = 165.35, p < .001, characterised by a significant linear performance decline as lag increased, F(1, 19) =

51.02, MSE = 127.44, p < .001; a marginally significant main effect of binding, F(1, 19) = 3.96, MSE = 103.23, p = .06, and a significant interaction between binding and lag, F(3, 57) = 3.95, MSE = 71.28, p < .05. Accuracy data as a function of lag are depicted in Figure 13 (Panel B).

Contrasts assessed the interaction between lag and binding, and indicated a marginally significant binding effect at the 250ms lag interval, F(1, 19) = 4.13, MSE = 85.14, p = .06; no binding effect at the 500ms lag interval, F(1, 19) < 1, a significant binding effect at the 2000ms lag interval, F(1, 19) = 8.01, MSE = 88.81, p < .05, and finally no binding effect at the 4000ms lag interval, F(1, 19) = 1.59, MSE = 89.20, p = .22. In sum, for accuracy measures, the effect of binding was only marginal, shown by post-hoc tests to be present for the 250ms and 2000ms lag intervals only, accounting for the interaction between lag and binding. For accuracy measures therefore, results suggested that binding may not have been maintainable over 4 seconds.

13.2.3. Assessing Negative Probe Performance

In the following analysis, performance for the two negative probe conditions was compared. The negative probe conditions in Series 1 indicated an asymmetry in the processing of shape and location features. The following analysis assessed whether a similar pattern of results ensued in Experiment 2A, where shapes only were task-relevant.

Reaction Time. RT measures for the both-features-new and new-shape conditions were subjected to a 4 (lag) x 2 (negative probe) ANOVA for repeated measures. The results indicated a significant main effect of lag, F(3, 57) = 4.55, MSE = 10650.58, p < .01; no significant main effect of negative probe, F(1, 19) < 1; and no interaction between factors, F(3, 57) < 1. Trend analysis indicated a significant linear trend, F(1, 19) = 5.98, MSE = 13520.24, p < .05; and a significant quadratic trend, F(1, 19) = 5.20, MSE = 12193.74, p < .05. Negative probe RT measures as a function of lag are presented in Figure 14A. The plot suggests a linear increase in RTs as lag increased, accompanied by a small decrease in RTs between the 250ms and 500ms lags, accounting for the quadratic trend. In sum, for RT measures there were no performance differences between the 250ms and 500ms lag intervals.



Figure 14. Experiment 2A - Negative probe performance. Panel A: A significant main effect of lag (p < .05), no significant main effect of negative probe (p > .05); and no interaction between factors (p > .05) for RT measures. Panel B: A significant main effect of lag (p < .05), no significant main effect of negative probe (p > .05); and no interaction between factors (p > .05) for accuracy measures (% correct). Bars represent one standard error of the mean.

Accuracy. Negative probe accuracy measures were subjected to a 4 (lag) x 2 (negative probe) ANOVA for repeated measures which indicated a significant main effect of lag, F(3, 57) = 4.45, MSE = 264.77, p < .01; no main effect of negative probe, F(1, 19) = 2.67, MSE = 131.35, p = .12, and finally, no interaction between factors, F(3, 57) = 1, MSE = 95.22, p = .26. Trend analyses on the main effect of lag indicated a significant linear trend, F(1, 19) = 6.12, MSE = 338.47, p < .05; and a significant cubic trend, F(1, 19) = 6.36, MSE = 217.59, p < .05. Negative probe accuracy measures are presented in Figure 14B as a function of lag. The linear trend suggests that overall, accuracy performance decreased as lag increased, although there was a small increase in accuracy between the 250ms and 500ms lags (particularly for new-shape probes), accompanied by a levelling off of performance (and slight increase for both-features-new probes) between the 2000ms and 4000ms lag intervals, accounting for the cubic trend.

13.3. Discussion

Experiment 2A yielded four key findings. The first was with regard to binding, which occurred automatically when shapes only were task-relevant (RT measures). The implication

is that when participants focussed on shape features, binding between the shapes and their respective spatial attributes occurred automatically. The binding which took place is automatic to the extent that under these conditions, it was not a strategy that aided performance (as the location stimuli were not task-relevant). Importantly, the size of the binding effect was similar to that found in Experiments 1A and 1B, in which both features were relevant and attended. However, robust binding effects were not noted for accuracy measures. This may be indicative of strategic differences between Experiment 1B and Experiment 2A (discussed in more detail below).

The second key result pertained to the persistence of binding over the lag intervals. Consistent with Experiment 1B, the intact over re-paired probe advantage for RT measures was present from the shortest lag interval (250ms) through to the longest (4000ms), indicating that the (automatic) binding between shape and location features occurred relatively early, and could be maintained for at least 4 seconds. One limitation to this interpretation, however, was the finding that there was no binding effect at the longest lag interval of 4000ms or at the 500ms lag interval for the accuracy measure.

That the binding effect was only present across all lag intervals in RT measures may indicate that the binding processed when shapes only were task-relevant was not quite as robust as that noted when both features were task-relevant (Experiment 1B). The two experiments may differ in terms of intent. In Experiment 1B, where both features were taskrelevant, the robust binding effects may reflect processing whereby participants strategically chose to bind shapes and locations. However, the binding in Experiment 2A may have reflected a more automatic process, in the absence of such intent. Alternatively, (or indeed additionally) the result may be indicative of RT measures being more sensitive to binding (a result echoing that found in Experiment 1B).

The third finding was of further evidence suggesting a period of short-term consolidation for items in the TBR array. The data was often characterised by an improvement in performance between the 250ms and 500ms lag intervals. As noted in the discussion of Series 1, this is consistent with the idea of a consolidation period, necessary for the encoding TBR items (e.g., Jolicoeur & Dell'Acqua, 1998; Jiang, 2004), which had not yet completed by 250ms.
Finally, the analysis of the negative probe conditions indicated no performance differences between the both-features-new condition and the new-shape condition. That performance did not differ between these two types of probe suggests that, contrary to the results of Experiment 1B, changing both features (shape and location) did not modify performance relative to changing only one feature (shape). This finding further points toward possible strategic differences between the two experiments. More specifically, the negative probe results of Series 1 indicated some conflict caused by a seen-before location, whereby the familiarity signal derived from the highly familiar location (occupied by a non-familiar shape) pushed participants to respond that they had seen both features before (i.e., to make an erroneous response). When shapes only were task-relevant, however, results indicated that presenting a new shape in an old location (new-shape probes) did not cause the same conflict, suggestive of the fact that participants did not rely so heavily on spatial location as a cue for response – a result which perhaps is not surprising given that the task entailed responding on the basis of shapes alone.

In summary, the results of Experiment 2A suggest that visual and spatial features were subject to binding processes, despite the fact that changes in location were taskirrelevant. In terms of the three experimental hypotheses, the task-relevance hypothesis, which stated that binding should only occur when both features were task-relevant (and thus predicted no binding effect in Experiment 2A), was rejected. Two experimental hypotheses remain: the automatic binding hypothesis and the asymmetry hypothesis. The automatic binding hypothesis predicts that the binding of shape and location features occurs automatically (perhaps as a result of the creation of an entirely new object representation in memory) and bi-directionally such that the encoding of feature A is accompanied by the encoding of feature B, and vice versa. The asymmetry hypothesis on the other hand predicts that the binding of shapes to locations occurs automatically when shapes only are taskrelevant, but not when locations only are task-relevant, and thus may be better characterised by links between features that are uni-directional. The hypothesis encompasses the idea of unequal contributions to binding of shape and location features (i.e., spatial location may be necessary in encoding object identity, while the reverse is not true e.g., Jiang et al., 2000; Olson & Marshuetz, 2005). Experiment 2B allowed the demarcation of these two contentions.

14. Experiment 2B

The aim of Experiment 2B was to assess the remaining two hypotheses pertaining to the nature of location binding; namely, the automatic-binding hypothesis, and the asymmetry hypothesis. In order to achieve this, in Experiment 2B locations only were task-relevant, while shape features were irrelevant. If binding effects are noted, strong evidence would have been gained for the automatic-binding hypothesis, suggesting that the binding between shape and location features occurs automatically in VSTM, and that both features do not have to be task-relevant in order to be bound. Conversely, if there is no evidence of binding when participants are instructed to focus on locations only, evidence would be consistent with the asymmetry hypothesis, and the idea of unequal contributions of shape and location features to binding, as noted in the location binding literature (e.g., Jiang et al., 2000; Olson & Marshuetz, 2005).

14.1 Method

Participants. Twenty undergraduate volunteers participated in the one hour experiment for course credit, or for a small honorarium. All participants reported normal or corrected-to-normal vision, and all were naïve to the aims of the experiment.

Materials. As in Experiment 2A.

Design and Procedure. Stimuli, task set up, trial construction and procedures were exactly as in Experiment 2A. The only difference was that participants were required to focus on locations only and to ignore the shapes. The three positive probe types were *intact* probes, *re-paired* probes and *new-shape* probes. The two negative probes were *bothfeatures-new* probes and *new-location* probes.

14.2 Results

14.2.1. Data Analysis

As in Experiment 2A, analyses encompass RT and accuracy measures. For each measure, the first analysis assessed whether there was evidence for binding, through

comparison of intact and re-paired probe conditions (Analysis 14.2.2; results assessing all three positive probe types can be found in Appendix F). Finally, performance for the two negative probe conditions was compared in Analysis 14.2.3. Descriptive statistics for all analyses are available in Appendix E.

14.2.2. Assessing Binding

Reaction Time. Intact and re-paired probe RT measures were subjected to a 4 (lag) x 2 (intact vs. re-paired probe) ANOVA for repeated measures. The analysis indicated no significant binding effect, F(1, 19) < 1; a significant main effect of lag, F(3, 57) = 4.63, MSE = 25880.08, p < .01, characterised by a significant quadratic trend, F(1, 19) = 5.76, MSE = 35417.55, p < .05, and a marginal cubic trend, F(1, 19) = 4.23, MSE = 9080.03, p = .05. Finally, these factors did not interact, F(3, 57) = 1.28, MSE = 4251.76, p = .29. The significant quadratic trend in the lag data was accounted for by a sharp improvement in performance between lags of 250 and 500ms. In sum, when focussing on locations, there was no evidence for binding in RT measures. The data are illustrated in Figure 15 (Panel A).

Accuracy. Intact and re-paired probe accuracy measures were subjected to a 4 (lag) x 2 (intact vs. re-paired probe) ANOVA for repeated measures, which indicated no significant binding effect, F(1, 19) = 2.36, MSE = 86.44, p = .14; a significant main effect of lag, F(3, 57) = 3.35, MSE = 115.43, p < .05, characterised by a significant linear trend, F(1, 19) = 4.59, MSE = 112.45, p < .05, and a marginal cubic trend, F(1, 19) = 3.99, MSE = 58.23, p = .06. Finally, the factors did not interact, F(3, 57) = 1.33, MSE = 64.00, p = .27. As in the RT analysis, there was no evidence for binding. The data are depicted in Figure 15 (Panel B).



Figure 15. Experiment 2B - The lack of binding in Experiment 2B. Panel A: A significant main effect of lag (p < .05); no significant main effect of binding (p > .05); and no interaction between factors (p > .05) for RT measures. Panel B: a significant effect of lag (p < .05); no significant main effect binding (p > .05); and no interaction between factors (p > .05); and no interaction between factors (p > .05) for accuracy measures (% correct). Bars represent one standard error of the mean.

Summary. When spatial locations were task-relevant and shapes were taskirrelevant, no evidence of location binding was found. Further, consistent with Experiment 2A, positive probe data suggested a period of performance improvement between the 250ms and 500ms lag intervals on both dependent variables.

14.2.3. Assessing Negative Probe Performance

Α

The present analysis assessed performance for the two negative probe conditions in order to establish whether there was any evidence of an asymmetry between the contributions of shape and location features, when locations only were task-relevant.

Reaction Time. Negative probe (both-features-new and new-location) RT measures were subjected to a 4 (lag) x 2 (negative probe) ANOVA for repeated measures. The analysis indicated a significant main effect of lag, F(3, 57) = 3.95, MSE = 52519.76, p < .05; no significant main effect of negative probe, F(1, 19) < 1; and finally, no interaction between factors, F(3, 57) = 1.39, MSE = 26322.61, p = .26. Trend analysis indicated a significant linear trend in the lag data, F(1, 19) = 14.00, MSE = 14390.92, p < .01. Negative probe

reaction time data as a function of lag are presented in Figure 16A. Inspection of this plot suggests a linear increase in RTs as lag increased. In sum, when focussing on locations only, no performance differences were present between the two negative probe conditions.



Figure 16. Experiment 2B - Negative probe performance. Panel A: A significant main effect of lag (p < .05); no significant main effect of negative probe (p > .05); and no interaction between factors (p > .05), for RT measures. Panel B: No significant main effect of lag (p > .05); no significant main effect of negative probe (p > .05); and no interaction between factors (p > .05), for accuracy measures (% correct). Bars represent one standard error of the mean.

Accuracy. Negative probe accuracy measures were subjected to a 4 (lag) x 2 (negative probe) ANOVA for repeated measures which indicated no significant main effect of lag, F(3, 57) = 1.89, MSE = 172.70, p = .14; no significant main effect of negative probe, F(1, 19) = 3.09, MSE = 146.40, p = .10, and finally no interaction between these factors, F(3, 57) = 1.11, MSE = 94.35, p = .35. The data are illustrated in Figure 16B. The accuracy data therefore reflect the RT data.

Summary. When locations only were the subject of the task, there were no performance differences between negative probe conditions. As in Experiment 2A, results are suggestive of the fact that in rejecting negative probes, performance depended only on judging the absence of the attended feature, and was not additionally modified by changes in the irrelevant feature.

14.3. Discussion

No evidence of binding was noted when participants were instructed to focus only on locations, indicating that the encoding and maintenance of the location attribute was not affected by irrelevant changes in the shape attribute, consistent with the findings of Jiang et al. (2000) and Olson and Marshuetz (2005). More specifically, the lack of an intact/re-paired probe difference suggests that no binding took place between shape and location features when locations only were attended. The automatic-binding hypothesis was rejected on these grounds.

The second point of interest arose from analysis of positive probe performance. There were significant trends in the lag data suggesting some performance improvement between the 250ms and 500ms lag intervals. As previously noted, this may reflect a period of consolidation, necessary for the encoding of the TBR array (e.g., Jolicoeur & Dell'Acqua, 1998; Jiang, 2004), discussed elsewhere. Interestingly, however, no such evidence was noted for negative probes. This stands in contrast to the results of the shape-relevant task (Experiment 2A), where negative probe performance was consistent with a period of consolidation. This is discussed in more detail below.

In sum, the results suggest that the asymmetry hypothesis was the best characterisation of location binding such that the encoding of visual identity necessarily entails the encoding of spatial location, while the reverse is not true.

15. Series Discussion

15.1. Summary of Findings

The results of Experiments 2A and 2B taken together suggest that the contribution of shape and location features to binding are not equal, consistent with the asymmetry hypothesis. No binding effect was observed when spatial locations were task-relevant and the shapes were irrelevant, suggesting that visual features are not processed and associated to their location in an automatic and obligatory fashion when not attended voluntarily. Binding between shapes and locations may occur automatically when focusing on shape information, but not when focusing on location information. The results suggest that location binding occurs when (1) both features are task-relevant (Series 1) and (2) when shapes only are task-relevant, but not when spatial locations are task-relevant (Experiments 2A & 2B, respectively).

The characteristics of the binding effect noted when shapes only were task-relevant were similar to those noted in Series 1, where both features were attended. More specifically, effect size computations estimated the effect for RTs to be similar in magnitude for the same dependent variable in Series 1; and secondly, the binding effect was present across all lag intervals, emerging within 250ms stimulus-offset, and maintaining for at least 4 seconds.

15.2. Differential Effects of Consolidation across Tasks

One may argue that the effect of lag qualitatively changed between Experiments 2A and 2B with regard to negative probes. More specifically, performance for negative probes in the shape-relevant task (Experiment 2A) was characterised by performance improvements between the 250ms and 500ms lag intervals, consistent with a period of consolidation (Jolicoeur & Dell'Acqua, 1998; Jiang, 2004). The same effect was absent for negative probes in the location-relevant task however (Experiment 2B), where lag performance was either characterised by a linear performance decline, or no effect of lag.

It is possible that the rates of decrement were different because the nature of material encoded and maintained in memory was different in the two experiments. For example, the TBR array in the shape-relevant task may have required more consolidation than was necessary in the location-relevant task (i.e., shape features may require more processing than location features). Further, if spatial location was indeed the more salient of the two

features, rejection of a probe on the basis of the familiarity signal emanating from a new location may have been carried out in a relatively fast manner. Indeed, as suggested by the presence of a binding effect in Experiment 2A and its absence in Experiment 2B, participants seemed to encode integrated information about shape and location where shapes were the attended feature, while they appeared to encode only the locations when spatial locations were the attended feature.

15.3. What Causes the Binding Asymmetry?

The implication of the results of Series 2 is that shape and location features do not become automatically integrated into 'object' type associations. If this was the case, binding effects should have been noted when shapes were the attended feature, *and* when locations were the attended feature. Rather, the data suggest that VSWM grants a role to both bound features, and features in isolation (Olson & Jiang, 2002), and were more consistent with the idea that location binding is characterised by the parallel storage of features that are bound together through feature links which are not weighted equally. Thus, location binding may constitute a functionally different type of binding than that observed for other visual features where reciprocal links are formed.

One explanation of the binding asymmetry is with regard to the salience of spatial location within visual cognition. In terms of Hommel's formulation of perceptual feature integration (event-files: Hommel, 2004; Hommel & Colzato, 2004), the results could be consistent with the contention that features are more likely to be bound if they are relevant for the completion of the task, or if an irrelevant feature is sufficiently prominent (spatial feature). The source of the spatial feature's prominence may be multiple. Firstly, the status of spatial location within visual cognition may be special and overpowering. For example, Hasher and Zacks (1979) cited spatial location as a type of stimulus event which is encoded in a relatively automatic manner. Additionally, it is possible that the location stimuli were more discriminable than the shape stimuli, so that locations may have constituted a better 'anchor' for binding (i.e., spatial location, as the more easily discriminated feature, may have served as a useful cue on which to differentiate between items).

A hint that changes in spatial location may have been more salient than changes in

shape identity was present in the analysis of negative probes in Series 1. There, participants were better at spotting a change in location, when shape remained consistent, than they were at identifying a change in shape when location remained consistent. Put simply, participants were more likely to erroneously respond that they had seen both features before based on the familiarity signal generated by the location feature than the shape feature.

The subject of stimulus discriminability is related to the more general issue of the attentional requirements entailed at encoding. The amount of attention necessary for the encoding of the shapes (as the harder attribute) may have been sufficient to induce the automatic encoding of the shapes' spatial location. Conversely, the encoding of spatial location may not have been so demanding as to induce the automatic encoding of item identity (shape). Additionally, if shape features were indeed difficult to discriminate from one another, the additional effort or attention dedicated to encoding these features may have resulted in the automatic processing of spatial location (see formulations of the 'attentional spotlight' e.g., Broadbent, 1982; Posner, 1980). Consistent with this contention is the finding that the encoding of shape information required more consolidation than that of the location information. A possible upshot of this is that the results may be perceptually grounded.

The hierarchical encoding view of the binding asymmetry (e.g., Jiang et al., 2000) suggests that the encoding of spatial location may be integral to the encoding of object identity, while the reverse is not true, thereby conditioning the direction of the association between the features. Additionally, the amount of attention allocated to a shape feature may also be shared by the location feature, by virtue of being encoded first. For example, in visual perception, Navon (1977) proposed that analysis of the global structure of a scene precedes the analysis of its local attributes. By this account, the processing of the shape attributes necessarily involves the processing of the global (location) attribute, before more fine-grained analysis of the shapes could take place. Support for this idea was recently suggested by Jiang et al. (2000). They proposed that when confronted with a display containing items in different locations, the spatial configuration of these items is first formed. Subsequently, visual attributes are bound to the respective parts of that configuration. The analysis of the spatial layout may therefore be a pre-requisite to the analysis of the local attributes. Participants in Experiment 2A would necessarily have had to analyse the spatial layout in order to ascertain

the visual identity of the constituent items. In Experiment 2B, a simple array-based configural representation of the items would suffice to perform the task. Consistent with this idea is the finding that processing latencies in Experiment 2B where location was task-relevant were numerically faster than those in Experiment 2A, where shape was task-relevant (although caution should be exercised in performing between-experiment comparisons of this nature).

Other research indicates that the asymmetry finding is not limited to the shape and location stimuli used here. For example, similar results were found by Jiang et al. (2000) using colour and location stimuli, and by Olson and Marshuetz (2005) using simplified faces in locations. The implication is that the asymmetrical relationship between visual identity and spatial location may be a general characteristic of visuo-spatial processing. Series 3 was designed to test in more detail the nature of the binding asymmetry between shape and location features.

SERIES 3: INVESTIGATING THE BINDING

ASYMMETRY

16. Series Introduction

The asymmetry findings of Series 2 were consistent with research from the fields of attentional selection and perceptual integration (e.g., in attentional selection: Lamy & Tsal, 2000; Hoffman & Nelson, 1981; Kim & Cave, 1995; in perceptual integration: Kahneman & Treisman, 1984; Treisman & Gelade, 1980; Treisman, 1998). Similarly, in the memory binding literature, evidence suggests a reliance on spatial location for the encoding of object identity, but not the reverse (e.g., Jiang et al., 2000; Olson & Marshuetz, 2005). The results suggest that rather than creating a whole new object representation, location binding may be better described by the parallel storage of features, which are bound via connections between features (e.g., Ruchkin et al., 2003; Wheeler & Treisman, 2002), but that the links are not necessarily reciprocal.

According to Jiang et al. (2000), the binding asymmetry arises as a result of hierarchical processing within VSWM. Spatial location is inseparably tied to object identity through the necessity to derive the spatial configuration of the scene before more fine grained analysis of the identity of those objects can take place. Conversely, object identity is not obligatorily associated to spatial location when the latter only is attended, as the processing of a spatial configuration occurs prior to analysis of what occupies its constituting locations (see also Navon, 1977). The asymmetry may further be driven by the relative automaticity of encoding spatial location features (e.g., Hasher & Zacks, 1979) versus the comparative difficulty with which item identity is derived. The binding asymmetry may therefore result from the interplay of two factors: 1) an hierarchical encoding of visuo-spatial features within the cognitive system and 2) the relative ease with which spatial locations are processed.

The aim of Series 3 was to investigate in more detail the characteristics of the asymmetrical relationship between shapes and locations. To achieve this, sixty shapes (taken from Vanderplas & Garvin, 1959) were piloted (Experiment 3A) in order to establish two sets of shapes: one 'easy' shape set (achieving high recall accuracy scores), and one

'hard' shape set (achieving significantly lower accuracy recall scores in a simple forced recognition task). Performance for the two sets of shapes was then contrasted in a shape-relevant task (Experiment 3B) and location-relevant task (Experiment 3C), analogous to Experiments 2A and 2B (Series 2).

One assumption of the hierarchical encoding account of location binding which can be tested empirically is the extent to which the binding of locations to shapes varies with the attentional demands of encoding the shape features. In order to process the shape information, location information has to be addressed first, resulting in the integration of (or linkages formed between) the shape and location features. If more attentional resources are allocated to the encoding of the shapes, then both shape *and* location features might benefit, enhancing the strength of the binding between the features. Processing more demanding shapes would result in more integration of the shape and the location features. Conversely, when locations only are task relevant, processing can stop at the spatial configuration stage and no link would need to be created to the shape feature. Under these circumstances, manipulating the amount of processing that would be necessary to encode the shape features (if they were to be attended) should have no effect on binding, as processing can stop at the spatial configuration stage.

Series 3 assessed this assumption, and made the following predictions. In Experiment 3B (participants attending to shapes), binding to location should take place, as shapes are the attended feature, and spatial location must be addressed first. Additionally, however, more binding should take place for the difficult shape set than the easy shape set by virtue of the fact that the former requires more processing than the latter. Importantly, the amount of processing received by the shape feature is also allocated to the location feature. Statistically therefore, one may expect a larger binding effect (i.e., a greater intact/re-paired probe difference) in the hard shape condition, relative to the easy shape condition. In short, the hierarchical encoding account predicts a significant main effect of binding and a significant interaction between shape difficulty and binding in Experiment 3B where shapes are attended.

In Experiment 3C (the location-relevant task), manipulating the relative difficulty of the shape features should not affect performance pertaining to binding, as encoding the spatial

locations can take place in isolation of the shape features occupying them. In Experiment 3C therefore, one may predict no significant main effect of binding, and no interaction between binding and shape difficulty.

17. Experiment 3A

The aim of Experiment 3A was to establish two sets of 16 shapes for use in Experiments 3B and 3C. To this end, sixty shapes (Vanderplas & Garvin, 1959) were piloted for difficulty in a shape recall task. Participants were presented with a single shape, and then following a lag interval, were asked to select the shape they saw from an array containing all possible shapes. Shapes to be used in the subsequent experiments were then selected on the basis of accuracy measures - sixteen shapes achieving relatively low (but above chance) accuracy scores formed the hard shape set; and sixteen shapes achieving relatively high accuracy scores formed the easy shape set. In order to ensure visual processing, the task was carried out under articulatory suppression, whereby participants repeated the words 'one-two' while shapes were on-screen and during a lag interval.

17.1 Method

Participants. Thirty-one volunteers participated in the thirty minute pilot experiment for a small honorarium. All participants had normal or corrected-to-normal vision, and all were naïve to the aims of the experiment.

Materials. All responses were collected via a computer mouse. Irregular black shapes (60) were taken from Vanderplas and Garvin (1959), who constructed shapes in accordance with the guidelines set out by Attneave (1957). In Vanderplas and Garvin (1959) each shape was created by plotting points selected from a table of random numbers on a 100 x 100 grid, which were then connected in-line with the following three rules: (a) The peripheral points were connected first to form a convex polygon. (b) The interior points were then randomly selected and connected one at a time to the sides at random. (c) After rule a and b, the line which defined the side to which the last point was connected was removed and the process repeated for the next point. Vanderplas and Garvin (1959) carried out this procedure for shapes comprising 4, 6, 8, 12, 16 and 24 points. In the present study, the 6 and 8 point sets were adopted (30 shapes in each), resulting in a total of 60 shapes. Shape stimuli are available in Appendix G. The task was purpose written using E-Prime.

Design and Procedure. The experiment began with a self-paced set of instructions informing participants that in each trial they would be presented with a single shape that they would have to commit to memory for a subsequent recall test. Participants were further informed that they would need to repeat the words 'one-two' while the memory item was on-screen, and during the lag interval. They were told that when the recall screen appeared, they were to select the shape they saw from the 60 in the grid by clicking on it with the mouse using the index finger of their dominant hand. A green frame appeared around the selected shape, indicating that a response had been collected.

The TBR shape was selected for presentation pseudo-randomly from a possible set of 60, with the constraint that each shape was presented three times across the experiment. Shape stimuli were filled in black, against a white background, and contained within a 20mm x 20mm black border. The recall screen consisted of all 60 shapes, positioned in a 10 x 6 matrix grid. The position of shapes within the grid was fixed across trials. The TBR shape was presented at the top centre of the screen, offset from the recall grid in order to prevent perceptual interference.



Figure 17. Experiment 3A - The time course of trials and an example of a 'correct' response.

Figure 17 illustrates the time course of a trial in Experiment 3A. Each trial began with

the presentation of the memory item appearing for 666ms. This was followed by a blank screen (lag interval) for 1000ms. The recall screen was then presented until participants made a response. The next trial was initiated automatically 500ms following a response. Participants were informed that the task was not speeded.

17.2. Results

Shapes to be included in the easy and hard sets in subsequent experiments were selected on the basis of accuracy scores achieved on the third presentation of each item, where participants were most likely to be familiar with the shapes. This procedure was thought to be representative of the forth-coming experiments where each shape was presented numerous times. Figure 18 depicts accuracy scores attained for each shape on the third presentation.

Accuracy scores for each shape (on the third presentation) were ranked. To compile the hard shape set, a lower-end cut off point of 60% accuracy was set and 16 shapes gaining 60% correct and upwards were selected. For the easy shape set, the 16 top scoring shapes on accuracy measures were selected (two shapes were excluded for resemblance to real world objects, e.g., mobile phone). Descriptive statistics for the two sets of shapes are presented in Table 2.



Accuracy as a Function of Shape

Figure 18 – Experiment 3A. Accuracy scores (proportion correct) attained on the third presentation for each shape used in Experiment 3A. Black bars denote the easy set and grey bars denote the hard shape set. White bars within the easy shape set indicate shapes dropped for resemblance to real world objects.

Easy Shapes				Hard Shapes		
(Proportion Correct)			(F	(Proportion Correct)		
Shape	M	SE	Shape	M	SE	
	.84	.07		.61	.09	
	.84	.07	1	.61	.09	
	.84	.07		.61	.09	
	.87	.06		.61	.09	
	.87	.06		.65	.09	
	.9	.05		.65	.09	
N	.9	.05		.65	.09	
	.9	.05		.65	.09	
	.9	.05		.65	.09	
7	.9	.05		.65	.09	
h	.9	.05		.65	.09	
	.94	.04		.65	.09	
L	.97	.03		.65	.09	
	.94	.04		.71	.08	
1	.97	.03		.74	.08	
	.97	.03		.74	.08	

Table 2. Descriptive statistics for shapes in the easy shape set, and hard shape set representing mean (M) accuracy scores (proportion correct), and standard error (SE).

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A t-test confirmed significant differences in accuracy scores between the easy and hard shape sets, t(15) = 45.68, MSE = .01, p < .001 (easy set: M = .90 SE = .01; hard set: M = .66, SE = .01). In sum, the pilot experiment outlined above allowed the establishment of two sets of 16 shapes (one easy set; and one hard set) to be contrasted in Experiments 3B and 3C.

18. Experiment 3B

Experiment 3B closely followed the procedure used in Experiment 2A (Series 2). Participants were instructed to focus on shapes only and to ignore locations. The shape stimuli comprised the easy and hard shape sets devised in Experiment 3A, and the spatial locations used were as in all previous experiments. The experiment took a 4 x 5 x 2 design, where shape difficulty was manipulated as a between-subjects factor, and probe type and lag The participants' task was to press 'yes' if the probe were within-subjects factors. represented a shape seen in the TBR array, and 'no' if it did not. The measure of binding was the difference in performance between the intact and re-paired probe conditions. The hierarchical encoding account of the asymmetry suggests that when focussing on shape features, spatial location becomes automatically integrated by virtue of the fact that analysis of the spatial configuration of the scene must precede the analysis of what occupies those locations. Thus, one would expect a significant binding effect in Experiment 3B regardless of shape difficulty. Additionally, however, the hypothesis holds that the amount of attention allocated for encoding the shapes dictates how much automatic encoding (and integration) the irrelevant location features will receive. Thus the hypothesis predicts a greater binding effect in the hard shape condition than in the easy shape condition, resulting in an interaction between binding and shape difficulty.

18.1. Method

Participants. Forty volunteers participated in the one hour experiment for a small honorarium. Twenty took part in the hard shape condition, and twenty in the easy shape condition. All participants reported normal or corrected-to-normal vision, and all were naïve to the aims of the experiment. Two participants from the easy shape condition and one from the hard shape condition were removed from statistical analyses for performance levels below that expected by chance.

Materials. Materials were as in Series 2 unless otherwise stated. The easy and hard shape stimuli were compiled as a result of Experiment 3A, and are available in Table 2.

Design and Procedure. The experiment took a 4 (lag) x 5 (probe type) x 2 (shape difficulty) design. Stimuli, trial construction and trial events were as in Experiment 2A (Series 2) unless otherwise stated. Participants were instructed to press 'yes' if the probe represented a shape they had seen in the TBR array, and 'no' if it did not. Series 1 ruled out verbal recoding as a mediator of performance pertaining to binding on this task. Nevertheless, as two new sets of shape stimuli were administered, Experiment 3B was carried out under articulatory suppression in order to prevent verbal recoding. The suppression task was to repeat the words 'one-two' while shapes were on-screen, and during the lag interval. The three positive probe conditions (requiring a 'yes' response) were: *intact* probes, *re-paired* probes and *new-location* probes. The two negative probes were *both-features-new* probes and *new-shape* probes.

18.2. Results

18.2.1. Data Analysis

As in previous experiments, median RT and accuracy measures (% correct) were analysed. Analysis 18.2.2 assessed the binding effect through comparison of intact and repaired probes, as a function of shape difficulty. Full analyses of all three positive probe types are presented in Appendix H. Finally, analysis 18.2.3 assessed negative probe performance in order to assess whether any evidence for an asymmetry in the encoding of shape and location features was present. Descriptive statistics for all analyses can be found in Appendix I.

18.2.2. Shape Difficulty and the Binding Effect

Reaction Time. To examine the effect of binding, RT data were subjected to a 4 (lag) x 2 (intact vs. re-paired probe) x 2 (shape difficulty) ANOVA for repeated measures, with shape difficulty as a between-subjects factor. The analysis indicated a marginally significant main effect of shape difficulty, F(1, 35) = 3.42, MSE = 291942.37, p = .07, whereby RTs were faster in the easy shape condition (M = 724.19, SE = 35.32) relative to the hard shape condition (M = 840.40, SE = 60.31). There was a significant main effect of binding, F(1, 35) = 15.83, MSE = 6138.60, p < .001; a significant main effect of lag, F(3, 105) = 2.89, MSE = 15.83, MSE = 6138.60, p < .001; a significant main effect of lag, F(3, 105) = 2.89, MSE = 15.83, MSE = 6138.60, p < .001; a significant main effect of lag.

21005.99, p < .05, characterised by a significant linear trend, F(1, 35) = 8.43, MSE = 21257.50, p < .01, and no interaction between lag and binding, F(3, 105) = 1.14, MSE = 4663.91, p = .34. Importantly, there was no interaction between binding and shape difficulty, F(1, 35) = .12, MSE = 6138.60, p = .74, suggesting that the binding effect was not modified by the set of shapes. Finally, there was no interaction between lag and shape difficulty, F(3, 105) = 1.12, MSE = 21005.99, p = .34, and no three-way interaction between lag, shape difficulty and binding, F(3, 105) < 1. Effect size computations (Cohen's *d*) estimated the binding effect for RT measures to be small in magnitude, d = .18.

A Priori Analyses. Given the specificity of the hypothesis it was important to verify whether a binding effect was observed for each shape condition separately. Within-subjects contrasts indicated a significant binding effect in the easy shape condition, F(1, 17) = 11.22, MSE = 1243.18, p < .01 (intact: M = 704.51, SE = 25.08; re-paired: M = 743.87, SE = 30.14). Similarly, there was a significant binding effect in the hard shape condition, F(1, 18) = 5.76, MSE = 1809.93, p < .05 (intact: M = 823.84, SE = 56.92; re-paired: M = 856.97, SE = 54.87). Panel A of Figure 19 depicts the binding effect as a function of lag for the easy shape condition; and Panel B the binding effect as a function of lag for the hard shape condition.

In sum, the analysis of the RT data indicated a significant binding effect, which was not modified by shape difficulty. In addition, performance was characterised by a linear increase in RTs as lag increased, but this decrement in performance did not mediate binding. Finally, that the easy shape set was indeed easier to remember than the hard shape set was reflected by longer response times for the latter.



Figure 19. Experiment 3B – The binding effect. Panel A: RT measures indicating a significant binding effect and a significant effect of lag (ps < .05) for the easy shape condition, with no interaction between factors (p > .05). Panel B: RT measures denoting a significant binding effect (p < .05), no significant effect of lag (p > .05) and no interaction between factors (p > .05) in the hard shape condition. Panel C: Accuracy measures indicating no significant binding effect for the easy shape condition (p > .05), a significant main effect of lag (p < .05) and no interaction between factors (p > .05): Panel D: Accuracy measures indicating a significant binding effect (p < .05) in the hard shape condition, with a significant main effect of lag (p < .05) and no interaction between factors (p > .05): Panel D: Accuracy measures indicating a significant binding effect (p < .05) in the hard shape condition, with a significant main effect of lag (p < .05), and no interaction between factors (p > .05). Bars represent one standard error of the mean.

Accuracy. A 4 (lag) x 2 (intact vs. re-paired probe) x 2 (shape difficulty) ANOVA for repeated measures, with shape difficulty as a between-subjects factor was computed for accuracy data. The analysis indicated no significant main effect of shape difficulty, F(1, 35) < 1 (easy shapes: M = 83.01, SE = 3.30; hard shapes: M = 80.70, SE = 2.94), a significant main effect of binding, F(1, 35) = 12.60, MSE = 83.38, p < .01, and a significant main effect of lag, F(3, 105) = 6.34, MSE = 134.51, p < .001, characterised by a significant linear decline in accuracy as lag increased, F(1, 35) = 16.07, MSE = 140.25, p < .001, and no interaction between lag and binding, F(3, 105) < 1. Importantly, there was no interaction between binding effect was not modified by varying the difficulty of the shape features (although see below). Finally, there was no interaction between lag and shape difficulty, F(3, 105) = 1.21, MSE = 134.51, p = .27. Effect size computations estimated the size of the binding effect to be medium in magnitude, d = .41.

A Priori Analyses. Similarly to the analysis of RT data, the specificity of the hypothesis rendered it necessary to assess whether binding was present in each shape condition. This was further bolstered by evidence from Figure 19 (panels C and D) which numerically suggested unequal amounts of binding in the easy and hard shape conditions. Contrasts indicated no significant binding effect in the easy shape condition, F(1, 17) = 2.29, MSE = 26.60, p = .15 (intact: M = 84.31, SE = 2.12; re-paired: M = 81.71, SE = 2.18); but a significant binding effect in the hard shape condition, F(1, 18) = 15.03, MSE = 15.41, p < .001 (intact: M = 83.17, SE = 2.12; re-paired: M = 78.23, SE = 2.22). Panel C of Figure 19 depicts the lack of binding as a function of lag for RT measures in the easy shape condition. Panel D depicts the binding effect as a function of lag for RT measures in the hard shape condition.

Summary. The results of Experiment 3B for RT measures suggested that binding took place in both the easy and hard shape conditions, and additionally, that the binding was not modified by lag. However, accuracy data suggested significant binding effects only for the hard shape condition, and not the easy shape condition.

18.2.3. Negative Probe Performance

The following analysis assessed performance for the two negative probe types. The aim was to establish if any evidence for an asymmetry in the encoding of shape and location features was present when shapes only were task-relevant.



Figure 20. Experiment 3B - Negative probe performance (collapsed across shape difficulty). Panel A: negative probe RT measures, indicating no significant main effect of probe (p > .05); and significant main effect of lag (p > .05); and no interaction between factors (p < .05). Panel B: Negative probe accuracy measures denoting a significant main effect of negative probe (p < .05); no significant main effect of lag (p > .05), and no interaction between factors (p > .05). Bars represent one standard error of the mean.

Reaction Time. Negative probe RT data were subjected to a 4 (lag) x 2 (negative probe) x 2 (shape difficulty) ANOVA for repeated measures, with shape difficulty as a between-subjects factor. Results indicated a significant main effect of shape difficulty, *F* (1, 35) = 5.69, *MSE* = 317203.04, p < .05, whereby reaction times were faster in response to easy shapes, relative to hard shapes (*M* = 800.57, *SE* = 28.60; *M* = 953.41, *SE* = 64.85, respectively). There was no significant main effect of negative probe, *F* (1, 35) = 1.75, *MSE* = 4190.20, p = .19; no significant main effect of lag, *F* (3, 105) = 2.11, *MSE* = 19025.67, p = .10; and the shape difficulty factor did not interact with the negative probe factor, *F* (1, 35) = 1.93, *MSE* = 4190.20, p = .17. Additionally, there was no significant interaction between lag and shape difficulty, *F* (3, 105) = 1.37 MSE = 19025.67, p = .26; no interaction between lag and negative probe, *F* (3, 105) = 1.35, *MSE* = 4092.16, p = .26; and finally, no three-way

interaction between factors, F (3, 105) < 1. Negative probe RT data, collapsed across shape difficulty conditions, are presented in Figure 20A.

Accuracy. Negative probe accuracy measures were subjected to a 4 (lag) x 2 (negative probe) x 2 (shape difficulty) ANOVA for repeated measures, with shape difficulty as a between-subjects factor. The analysis indicated no significant main effect of shape difficulty, F(1, 35) = 2.81, MSE = 1318.63, p = .10 (easy shapes: M = 75.93, SE = 3.36; hard shapes: M = 68.86, SE = 4.25). There was a significant main effect of negative probe, F(1, 35) = 13.48, MSE = 144.64, p < .01, whereby performance was superior in the both-feature-new condition (M = 74.90, SE = 2.51) relative to the new-shape condition (M = 69.70, SE = 3.05); no significant main effect of lag, F(3, 105) = 1.02, MSE = 163.26, p = .39; and no interaction between negative probe and lag, F(3, 105) < 1. Finally, there was no interaction between lag and shape difficulty, F(1, 35) = 2.63, MSE = 144.64, p = .11; and no three-way interaction between factors, F(3, 105) < 1. Negative probe accuracy data (collapsed across shape difficulty) are presented in Figure 20B. Effect size computations (Cohen's d) estimated the difference between both-features-new probes and new-shape probes to be small in magnitude, d = .31.

Summary. For RT measures, there were no performance differences between the two negative probe conditions; however, accuracy measures indicated superior performance in the both-features-new condition relative to the new-shape condition across all lag intervals.

18.3. Discussion

The results of Experiment 3B yielded two key findings. Firstly, binding was present across lag intervals in both the easy and hard shape conditions. However, analyses of the accuracy data suggested that the binding effect was only significant in the hard shape condition. The results suggested that some binding between shape and location features took place automatically when shapes only were attended, but that the strength of the binding which emerged varied with the difficulty of the shape features. Thus the results of Experiment 3B support the prediction made by the hierarchical encoding account set out above. In order to be meaningful, however, the results of Experiment 3B (shape-relevant task) need to be taken in concert with those of Experiment 3C (location-relevant task), presented below.

Secondly, findings from the negative probe analysis were consistent with the contention that even though shapes only were task-relevant, some encoding of spatial location took place automatically. For accuracy measures, rejecting a new shape was harder when it was presented in a familiar location, indicating that the location could not be ignored.

19. Experiment 3C

The aim of Experiment 3C was to assess whether there would be evidence for location binding when spatial location only was task-relevant and shape stimuli varied in difficulty. Our hierarchical formulation of the binding asymmetry suggests that spatial location is encoded together with visual features whenever the latter are attended, but that the encoding of spatial location can be carried out in isolation when visual features are not relevant for task completion (e.g., Jiang et al., 2000). Additionally, if spatial locations are indeed processed in isolation of shape features, manipulating the relative difficulty of the shape features should not affect performance on this task. The hierarchical account of the binding asymmetry therefore predicts that there should be no significant binding effect, and no interaction between binding and shape difficulty in Experiment 3C.

19.1. Method

Participants. Forty volunteers participated in the one hour experiment for course credit, or for a small honorarium. Twenty took part in the hard shape condition, and twenty in the easy shape condition. Two participants from the easy shape condition; and two from the hard shape condition were removed from statistical analysis for performance levels below that expected by chance, resulting in n = 18 in both conditions. All participants reported normal or corrected-to-normal vision, and all were naïve to the aims of the experiment.

Materials. As in Experiment 3B.

Design and Procedure. Stimuli, task set-up, trial construction and procedures were as in Experiment 3B unless otherwise stated. Participants were informed that they would be required to focus on locations only. The three positive probe types were: *intact* probes, *repaired* probes, and *new-shape* probes. The two negative probes were *both-features-new* probes and *new-location* probes.

19.2. Results

19.2.1. Data Analysis

As in previous experiments RT and accuracy measures are presented. Analysis 19.2.2 assessed the binding effect as a function of shape difficulty, through comparison of intact and re-paired probes. Full analyses of all three positive probe types are presented in Appendix J. Finally, analysis 19.2.3 assessed negative probe performance in order to ascertain whether there was any evidence for the incidental encoding of the shape features when locations only were attended. Full descriptive statistics for Experiment 3C are presented in Appendix K.

19.2.2. Shape Difficulty and the Lack of Binding Effect

Reaction Time. RT data were subjected to a 4 (lag) x 2 (intact vs. re-paired probe) x 2 (shape difficulty) ANOVA for repeated measures, with shape difficulty as a between-subjects factor. The analysis indicated no significant main effect of shape difficulty, F(1, 34) = .000, MSE = 248960.93, p = .99 (easy shapes: M = 631.31, SE = 56.84; hard shapes: M = 631.66, SE = 28.05); no significant main effect of binding, F(1, 34) < 1, but a significant main effect of lag, F(3, 102) = 8.05, MSE = 11859.75, p < .001, characterised by a significant linear trend, F(1, 34) = 20.88, MSE = 10294.28, p < .001, and a significant cubic trend, F(1, 34) = 1.67, MSE = 14839.61, p < .05. RT measures for intact and re-paired probes as a function of lag are presented in Figure 21A for the easy shape condition, and in Figure 21B for the hard shape condition. The linear trend in the lag data was accounted for a general increase in RTs as lag increased, whereas the cubic trend was accounted for by a tendency for RT performance to improve between the 250 and 500ms lag intervals.

Additionally, there was no interaction between lag and shape difficulty, F (3, 102) = 1.17, MSE = 11859.75, p = .32; no interaction between binding and shape difficulty, F (1, 34) = 1.56, MSE = 2739.65, p = .22, but a significant interaction between lag and binding, F (3, 102) = 3.45, MSE = 1996.46, p < .05. The three-way interaction between factors was non-significant, F (3, 102) = 2.24, p = .09. Contrasts assessed the interaction between binding and lag, and indicated no significant binding effect at the 250ms lag interval, F (1, 34) < 1; no significant binding effect at the 500ms lag interval, F (3.08) < 1, no binding effect at the

2000ms lag interval, F(1, 34) < 1, but a significant re-paired over intact probe advantage at the 4000ms lag interval, F(1, 34) = 6.80, MSE = 1912.47, p < .01.

A Priori Analyses. As in Experiment 3B, the specificity of our hypothesis meant that it was necessary to determine whether there was evidence for binding in each shape set. Contrasts indicated no significant binding effect in the easy shape condition, F(1, 17) < 1 (intact: M = 629.19, SE = 52.57; re-paired: M = 633.44, SE = 56.50); and no significant binding effect in the hard shape condition, F(1, 17) = 1.41, MSE = 796.41, p = .25 (intact: M = 637.25, SE = 22.89; re-paired: M = 626.08, SE = 22.62). In sum, the RT data indicated that when locations only were task-relevant, there was no evidence for binding between locations and shapes, whether the shapes were from the easy or hard set.

Accuracy. Accuracy data were subjected to a 4 (lag) x 2 (intact vs. re-paired probe) x 2 (shape difficulty) ANOVA for repeated measures, with shape difficulty as a betweensubjects factor. The analysis indicated a significant main effect of shape difficulty, F(1, 34) = 6.64, MSE = 136.65, p < .01, whereby accuracy was significantly better in the hard shape condition (M = 90.80, SE = 1.61) relative to the easy shape condition (M = 87.26, SE = 2.21). There was no significant main effect of binding, F(1, 34) < 1, and a significant main effect of lag, F(3, 102) = 6.86, MSE = 78.60, p < .001, characterised by a significant linear trend F(1, 34) = 16.92, MSE = 77.95, p < .001, and a marginally significant cubic trend, F(1, 34) = 3.61, MSE = 82.61, p = .07. Additionally, there was no significant interaction between lag and shape difficulty, F(3, 102) = 1.52, MSE = 78.60, p = .21; no interaction between binding and shape difficulty, F(1, 34) < 1; and a significant interaction between lag and binding, F(3, 102) = 1.52, MSE = 78.60, p = .21; no interaction between binding and shape difficulty, F(3, 102) = 1.52. Finally, there was a marginal three-way interaction between factors, F(3, 102) = 2.97, p = .05. Accuracy measures for intact and re-paired probes as a function of lag are presented in Figure 21C for the easy shape condition, and Figure 21D for the hard shape condition.



Figure 21. Experiment 3C. The lack of binding effect. Panel A: RT measures indicating no significant binding effect (p > .05); a marginal main effect of lag (p = .08); and a significant interaction between factors (p < .05) for the easy shape condition (p > .05). Panel B: RT measures denoting no significant binding effect (p > .05); a significant main effect of lag (p < .05) and a marginally significant interaction between factors (p = .07) for the hard shape condition. Panel C: Accuracy measures indicating no significant binding effect (p > .05); a significant main effect of lag (p < .05) and a marginal interaction between factors (p = .09) for the easy shape condition: Panel D: Accuracy measures indicating no significant binding effect (p > .05); a significant main effect of lag (p < .05), and a significant interaction between factors (p < .05) in the hard shape condition. Bars represent one standard error of the mean. Contrasts assessing the interaction between lag and binding indicated no intact/repaired difference at the 250ms lag interval, F(1, 34) = 1.54, MSE = 48.57, p = .22; a significant re-paired over intact probe advantage at the 500ms lag interval, F(1, 34) = 14.96, MSE = 20.04, p < .001; no probe differences at the 2000ms lag interval, F(1, 34) < 1; and finally, no difference between intact and re-paired probes at the 400ms lag interval, F(1, 34) = 1.62, MSE = 65.41, p = .21. The interaction between lag and binding therefore was sourced by a re-paired over intact probe advantage at the 500ms lag interval.

A Priori Analyses. Contrasts examined whether there was evidence for binding in the easy and hard shape conditions separately. Analyses indicated no significant binding effect in the easy shape condition, F(1, 17) < 1 (intact: M = 87.24, SE = 1.44; re-paired: M = 87.27, SE = 1.10); and no significant binding effect in the hard shape condition, F(1, 17) < 1 (intact: M = 90.83, SE = .91; re-paired: M = 90.78, SE = .78). In sum, there was no evidence of binding for accuracy measures when locations only were task-relevant, for either the easy shape or hard shape condition.

19.2.3. Negative Probe Performance

In Experiment 3B, the analysis of negative probe performance suggested some encoding of location information when shapes were task-relevant (i.e., a both-features-new over new-shape probe advantage). The following analysis aimed to establish whether a mirror pattern of results was present when locations only were task-relevant, or whether shape information in these circumstances could be disregarded.

Reaction Time. A 4 (lag) x 2 (negative probe) x 2 (shape difficulty) ANOVA for repeated measures, with shape difficulty as a between-subjects factor was computed for RT measures. The analysis indicated no significant main effect of shape difficulty, F(1, 34) < 1(easy shapes: M = 681.44, SE = 54.87; hard shapes: M = 683.50, SE = 29.90); no significant main effect of negative probe, F(1, 34) < 1; but a significant main effect of lag, F(3, 102) =5.03, MSE = 19050.43, p < .01, characterised by a significant linear trend, F(1, 34) = 9.60, MSE = 7416.84, p < .01; a significant quadratic trend, F(1, 34) = 5.27, MSE = 20644.26, p < .05, and a marginal cubic trend, F(1, 34) = 3.85, MSE = 12376.28, p = .06. There was no interaction between lag and shape difficulty, F(3, 102) < 1; no interaction between negative probe and shape difficulty, F(1, 34) < 1; no interaction between lag and negative probe, F(3, 102) < 1; and finally, no three-way interaction between factors, F(3, 102) < 1. Negative probe RT data, as a function of lag are presented in panel A of Figure 22 (collapsed across easy and hard shape conditions).

In sum, for RT measures there were no performance differences between negative probe types. Finally, lag data indicated linear, quadratic, and cubic (marginal) trends in the data. The cause of these trends is more apparent in the new-location condition where performance appeared to worsen between the 250 and 500ms lag intervals, improve at the 2000ms lag interval, then declined again to the 4000ms interval.

Accuracy. A 4 (lag) x 2 (negative probe) x 2 (shape difficulty) ANOVA for repeated measures with shape difficulty as a between-subjects factor indicated a marginal main effect of shape difficulty, F(1, 34) = 3.06, MSE = 354.15, p = .09 (easy shapes: M = 81.93, SE = 2.75; hard shapes: M = 85.81, SE = 2.38); a significant main effect of negative probe, F(1, 34) = 6.85, MSE = 62.95, p < .05, whereby performance was superior in the both-featuresnew condition (M = 85.09, SE = 1.64) relative to the new-location condition (M = 82.64, SE = 2.06); and a significant main effect of lag, F(3, 102) = 9.02, MSE = 108.35, p < .001, characterised by a significant linear trend, F(1, 34) = 5.71, MSE = 110.49, p < .05; a significant quadratic trend, F(1, 34) = 12.51, MSE = 125.83, p < .01; and a significant cubic trend, F(1, 34) = 8.58, MSE = 88.73, p < .01. Additionally, there was no interaction between negative probe and lag, F(3, 102) = 1.07, MSE = 108.35, p = .14; no interaction between negative probe and shape difficulty, F(1, 34) < 1; and finally, no three-way interaction between negative probe and shape difficulty, F(1, 34) < 1; and finally, no three-way interaction between negative probe and shape difficulty, F(1, 34) < 1; and finally, no three-way interaction between negative probe and shape difficulty, F(1, 34) < 5.7, p = .35.

For accuracy measures therefore, the data indicated significantly superior performance in the both-features-new condition, relative to the new-location condition. However, inspection of Figure 22B suggests that this effect was largely due to differences at the 2000ms lag interval. Finally, the lag data indicated linear, quadratic and cubic trends in

the data. Similarly to previous experiments, the trends appear driven by a large improvement in accuracy between the 250 and 500ms lag intervals.



Figure 22. Experiment 3C - Negative probe performance. Panel A: Negative probe RT measures as a function of lag, collapsed across shape difficulty. Panel B: Negative probe accuracy measures as a function of lag, collapsed across shape difficulty. Bars represent one standard error of the mean.

Summary. For RT measures there were no performance differences between the two types of negative probe. For accuracy measures however, performance where both features were new was superior to where a new location was occupied by an old shape. However the difference appeared to be restricted to the 2000ms lag interval. Additionally, both accuracy and RT measures indicated linear, quadratic and cubic (only marginally significant for RTs) trends in the data. For accuracy measures, the cause of the trends appears to be driven by an improvement in performance between the 250ms and 500ms lag intervals.

19.3 Discussion

Experiment 3C yielded two key findings. Firstly, when spatial location was the object of the task, no binding took place between the spatial locations and the shapes occupying them. The findings suggest that when focussing on spatial location, the information could be encoded in isolation of the shape features (e.g., Jiang et al., 2000), regardless of whether shapes were easy or hard to encode. The second key finding pertained to negative probe performance. RT and accuracy measures indicated that both-features-new and new-location probe performance did not differ across lag intervals (with the exception of the 2000ms lag interval in RT measures). The finding suggests that, with the exception of the 2000ms lag, a seen-before shape (in a new location: new-location probes) did not result in a familiarity signal strong enough to push participants to erroneously indicate that they had seen the location before.

One additional result deserving further commentary was with regard to the shape difficulty manipulation in this experiment. Analysis indicated superior performance for the hard shape condition relative to the easy shape condition for positive probe accuracy measures. The reason for superior performance in judging spatial location in the hard shape condition relative to the easy shape condition remains unclear. Given that this result is somewhat counterintuitive, a word of caution should accompany the conclusions from this experiment. Indeed, one possible caveat to the shape selection procedure adopted in Experiment 3A is that it is difficult to establish what the performance differences between the two sets of shapes in that experiment represent. More specifically, in that task shapes were recalled within the context of all possible shapes, whereas in Experiments 3B (shapes were irrelevant in Experiment 3C) memory for shapes was tested within each set. It is possible, therefore, that the two sets of shapes vary on a dimension other than encoding difficulty. Thus, rather than representing subsets of easy-to-encode and a hard-to-encode shapes, the shapes in each set may differ with regard to the ease with which they were discriminated from other shapes. Future experimentation should assess more stringently what differences in shape performance actually represent.

Nevertheless, the shape manipulation resulted in differential effects of binding where shapes only were attended (Experiment 3B) while no evidence for binding was noted in either the easy or hard shape conditions when locations only were attended (Experiment 3C), indicating that the overall conclusion drawn from that analysis was not compromised.

20. Series Discussion

20.1. Summary of Findings

Series 3 sought to gain further insight into the binding asymmetry noted in Series 2. The results indicated that when shapes only were task-relevant (Experiment 3B), binding to location occurred automatically, whether shapes were from the easy or hard shape set. Additionally, accuracy measures indicated that the strength of the binding varied with shape difficulty, suggesting that the more attention allocated to encoding visual identity, the greater the binding of visual identity to spatial location, even though the latter was irrelevant for task completion. Furthermore, negative probe data suggested that when shapes were taskrelevant, the encoding of spatial location occurred automatically by virtue of the fact that performance for the new-shape (old location) condition was poorer than in the both-featuresnew condition across all lag intervals. This finding suggests that the familiarity signal emanating from the seen-before location pushed participants to erroneously respond that they had seen the shape feature before, even though locations were not task-relevant, further strengthening the claim that in encoding object identity (shape), spatial location is obligatorily processed. Finally, in the location-relevant task (Experiment 3C), no evidence for binding was noted in either the easy or hard shape conditions, suggesting that the location information could be maintained independently of the shapes occupying them. The results of the shape-relevant task (Experiment 3B) and the location-relevant task (Experiment 3C) taken together support the hierarchical hypothesis of the binding asymmetry (although note the criticism of the shape selection task in Experiment 3A on page 128).

20.2. Hierarchical Encoding and the Binding Asymmetry

Our findings are consistent with those of Jiang et al. (2000) who suggested that on encountering a visual array of objects, what is first formed is a configuration of the spatial layout of items, and that subsequently, features of the objects occupying the spatial locations are linked to the respective parts of the configuration. In short, the formation of a spatial configuration of items is a relatively automatic process, and the derivation of the constituent features of the configuration may require an extra processing stage. In terms of the locationrelevant task, processing could stop at the point where a spatial configuration of items was formed, explaining why no binding took place between locations and shapes. Conversely, in the shape-relevant task, processing of the shapes entailed the integration of the respective spatial locations. Supportive of this contention, and consistent with the findings of Series 2, is the observation that RTs in the location-relevant task were numerically faster than in the shape-relevant task. Other lines of research have provided similar findings using different visuo-spatial stimuli (e.g., colour and location: Jiang et al., 2000; simple face stimuli and location: Olson & Marshuetz, 2005). The binding asymmetry may therefore be a general characteristic of visuo-spatial processing, and not simply an artefact of our shape and location stimuli. Importantly, our results provided additional evidence that in the shape-relevant task, the encoding demands of the shape features mediated the amount of binding which took place between shapes and locations. This finding is consistent with the idea that spatial location is inseparably tied to object identity, and that increasing the amount of processing necessary for the attended feature (shape) also enhanced the processing of the unattended feature (spatial location) thus increasing the size of the binding effect.

20.3. Binding and Attentional Resources

The findings from the shape-relevant task (Experiment 3B) deserve additional theoretical consideration. That more binding ensued in the hard shape condition than the easy shape condition can be explained in terms of the literature on attentional selection (although note the criticism of the shape selection task outlined above). There, evidence suggests that selection occurs via the direction of an attentional spotlight (e.g., Broadbent, 1982; Posner, 1980). Objects falling under the spotlight are subject to processing with priority. If, in the hard shape condition, the spotlight lingered for longer, spatial location (by virtue of being obligatorily processed along with shape features) may have benefited through this process. This finding supports the contention that binding in working memory may benefit from attentional resources – the more attention allocated to encoding shapes, the greater the binding between the shapes and the locations, and is contrary to recent investigation by Allen et al. (2006) who found that binding between colour and shape attributes was not disrupted by a variety of attentionally demanding concurrent tasks. The issue of attentional contribution to location binding is investigated in Series 4.
SERIES 4: IS LOCATION BINDING ATTENTIONALLY

DEMANDING?

21. Experiment 4

Experiment 4 sought to address directly the issue of whether location binding is attentionally demanding. The results of Series 2 and 3 suggest that some binding takes place automatically when shapes are the attended feature, but not when locations are the attended feature, suggesting some obligatory automatic binding in the former but not the latter. Experiment 4 investigated whether the binding demonstrated in Series 1 (Experiment 1B: when both features were task-relevant) occurred as a result of obligatory automatic processing, or whether additional attentional resources were employed. The issue of the contribution of attentional resources to binding is a key theoretical question pertaining to the mode of storage of visuo-spatial features in WM, and is particularly pertinent given the newly proposed episodic buffer (EB) component of the working memory model. The EB was proposed to account for evidence that disparately processed information can be integrated in memory (Baddeley, 2001), and is assumed to serve the binding function through the integration of information from the phonological loop, the visuo-spatial sketchpad and from long-term memory. One key constraint of the original formulation of the EB is that access can only be achieved via the central executive "[the buffer]...is assumed to be controlled by the central executive, which is capable of retrieving information from the store in the form of conscious awareness, of reflecting on that information and, where necessary, manipulating and modifying it." (Baddeley, 2001; pp 421). Consequently, one functional limitation to the maintenance of bound representations under the EB formulation is that processing is constrained by available central executive resources.

Consistent with this supposition, numerous authors have found evidence in agreement with the notion that feature binding requires focussed attention (e.g., Wolfe, 1999; Wheeler & Treisman, 2002). Additional support for the involvement of the central executive in binding has been found in neuropsychological studies suggesting a role for the prefrontal cortex in executive functions (e.g., Baddeley, 1986) but also in feature integration (e.g.,

Prabhakaran et al., 2000; Simon-Thomas et al., 2003).

However, not all evidence is supportive of the idea that binding requires attentional resources. For example, Allen et al. (2006) failed to find an effect of an attentional manipulation on memory for integrated colour and shape attributes (i.e., memory for bound representations were not disrupted by attentionally demanding secondary tasks any more than for individual colour or shape features).

Allen et al.'s (2006) shape condition involved the presentation of four shapes in a single colour. At test, participants had to decide whether a single probe shape was one which was to-be-remembered. In their colour condition, four coloured squares were presented, and participants judged whether a single probe square was in the same colour as one presented in the to-be-remembered array. In their combination condition, four coloured shapes were presented, and participants had the task of judging whether a single probe represented an original colour-shape combination seen in the TBR array. In order to test binding, probes including a switched colour and shape were included. Finally, in their either condition, four coloured shapes were presented, and participants did not know which feature (colour or shape) would be tested until the probe appeared. The results of Allen et al.'s (2006) Experiment 1 indicated a binding effect, whereby performance did not differ between the single feature shape condition (the more difficult of the two single feature conditions), and the combination condition, where participants were constrained to remember associations between features.

Their second experiment assessed the extent to which the binding noted in their first experiment was automatic, by pairing the task with an attentionally demanding secondary task (requiring participants to count backwards in 1's). Their data indicated again a significant binding effect, but in addition, the secondary task did not affect performance in the combination condition more than in the single feature conditions. Their third and fourth experiments used the same experimental procedure, with more demanding secondary tasks: near span recall of a string of digits, and concurrently counting backwards in 3's. Findings again indicated that the binding between colour and shape features was not disrupted any more than was memory for single features, indicating that the visuo-spatial binding of colour and shape attributes was not dependent on attentional resources any more than the

maintenance of the composite features.

The authors acknowledged that there may be a distinction between binding which occurs automatically (underpinning their shape to colour binding results), and attentionally demanding (effortful) binding processes, the latter (but not the former) of which are assumed to be processed within the buffer. To date, however, the conditions conducive to automatic versus effortful binding remain unclear. One assertion is that the binding between visuospatial feature attributes occurs automatically by virtue of being perceived as belonging to the same object. In Chapter 4, two types of binding were delineated; 'property bindings' (where features to be integrated form properties of an object, e.g., a coloured square) were shown to be better maintained in memory than 'part bindings' (where properties to be integrated appear on different parts of the same object; e.g., Xu, 2002b). Further, this property binding advantage may be bolstered by perceptual unitisation - that features are more likely to be integrated if they are perceived to belong to the same object - (e.g., Asch et al., 1960; Ceraso et al., 1998; Delvenne & Bruyer, 2004). The stimuli used by Allen et al. (2006) comprised shape and colour attributes, by definition constituting property binding (as the colour is a property of the shape feature), the binding of which may ensue in a relatively automatic and obligatory fashion, consistent with their bound representations resilience to various attentionally demanding tasks. One contention, therefore, is that binding taking place in memory as a result of perceptual unitisation may not require attentional resources. However, other types of binding in memory may require such resources.

More specifically, evidence suggests that location binding may represent a functionally distinct class of binding by virtue of asymmetries in contribution from visual and spatial features (e.g., Series 1, 2 & 3 of the present thesis; Jiang et al., 2000; Olson & Marshuetz, 2005). Series 2 demonstrated the automatic nature of location binding when shapes were task-relevant, but not when locations were task-relevant. Additionally, Series 3 replicated this finding, and further provided evidence that additional attentional resources may enhance the binding which took place automatically (when shapes only were task-relevant).

The updated WM framework (e.g., Baddeley, 2001) predicts that effortful (possibly mnemonic) binding takes place within the EB, and is constrained by the availability of attentional resources from the central executive. However, automatic (possibly perceptual in

origin) binding may take place elsewhere (e.g., in the visuo-spatial sketchpad, Allen et al., 2006). One key prediction of effortful binding within the buffer is that it should be disrupted by an attentionally demanding concurrent task. Conversely, automatic binding would not fall under the control of the EB, and may therefore be resilient to such a task. Experiment 4 capitalised on this key assumption, utilising the paradigm used in Experiment 1B, paired with an attentionally demanding secondary task. Three shapes (as used in Series 1) were presented simultaneously in different locations, and participants had the task of indicating whether a single probe item comprised *both* a shape and location seen in the TBR array on that trial, regardless of whether the features were initially presented as part of the same object.

In selecting the secondary task, care was taken to ensure that any potential interference elicited by it would reflect the mobilisation of attentional resources rather than item-based interference (for example due to stimulus similarity; e.g., Baddeley, 1966; Hitch, et al., 1998). To this end, a secondary task involving verbal stimuli was preferred. This task consisted of the requirement for participants to maintain a string of digits in serial order (presented at the start of each trial) while performing the visuo-spatial probe task (Lavie & de Fockert, 2005). Trials proceeded as in Experiment 1B with the difference that a to-be-remembered digit string was presented before each probe trial and memory for this string was tested after the participant's response to the probe task. In the digit recall task, a single digit appeared at the centre of the screen. Participants were asked to indicate (by way of a key press) which number came next in the sequence they were retaining. As the maintenance of the string of numbers entailed not only a memory load, but also required the maintenance of digit serial position, it was expected to load on attentional resources as the task was effortful.

If binding to location proceeds automatically and effortlessly by virtue of features being perceived as part of the same object there should be no detrimental effect of the concurrent attentionally demanding task on binding. If findings are consistent with this supposition, the implication would be that location binding in memory may represent a type of automatic binding, perhaps fostered by perceptual unitisation that occurs outside of the control of the EB, consistent with the findings of Allen et al. (2006). Additionally, if binding to location is effortful there should be a detrimental effect of the attentionally demanding task on

binding. If results are consistent with this supposition, the implication would be that location binding may be overseen by the EB component of the WM model, which may contribute to binding through provision of attentional resources (perhaps supporting strategic processing).

21.1. Method

Participants. Eighty undergraduate volunteers (40 in the no-load condition, and 40 in the load condition) participated in the one and a half hour experiment for course credit or for a small honorarium. All participants reported normal or corrected-to-normal vision, and all were naïve to the aims of the experiment. One participant was dropped from the analysis of the load condition for scoring well below chance for one or more probe types on trials in which the digit load probe was responded to correctly, resulting in n = 39 in the load condition.

Materials. As in Experiment 1B (Series 1).

Design and Procedure. The experiment took the form of a 4 (lag) x 5 (probe type) x 2 (load versus no load) design, with load as a between-subjects factor. Stimuli, trial construction and trial events were as in Experiment 1B, unless otherwise stated. In the load condition, in addition to the probe task, participants had to remember a string of five digits which appeared onscreen at the start of each trial (Lavie & de Fockert, 2005; replaced by a string of stars in the control condition). At the end of each trial, a single number appeared onscreen and participants had the task of indicating, via a key press, which number came next in the string of numbers they were maintaining. Digit strings always began with a zero, and the remaining four digits were randomly sampled from numbers 1 to 4 without replacement on each trial. The load probe was selected pseudo-randomly from the first 4 digit positions.



Figure 23. Experiment 4 - The time course of a single trial in Experiment 4 (trial type presented represents an intact probe trial, and would be correctly responded to with a 'yes' response. Additionally, the correct response for the load probe would be '3').

Participants were instructed that the primary task was to press 'yes' if the probe represented a shape and location that they had seen before in the TBR array, irrespective of whether they were originally presented together on that trial, and to press 'no' otherwise. The two positive probe types were: *intact* probes and *re-paired* probes. The three negative probe conditions comprised *both-features-new* probes, *new-shape* probes and *new-location* probes.

Figure 23 illustrates the time course of a single trial in Experiment 4 (the trial represented is an intact probe trial). Each trial began with the simultaneous presentation of a string of 5 digits, which always began with a zero, for 2500ms (replaced by a string of stars in the control condition), followed by a blank screen (1000ms), then a TBR array of three shapes in locations (2000ms). At the offset of this display a visual mask flashed onscreen for 150ms, and then there was a lag interval (inclusive of the mask) which varied between 250ms, 500ms, 2000ms and 4000ms (blocked). A single probe item was then presented until participants made a response. At the offset of the single probe item, as in previous experiments, accuracy feedback was presented for 1500ms (consisting of accuracy on the previous trial). Finally, in the attentional load condition, the load (digit) probe was presented

(not presented in the control condition, and the following trial proceeded at this point), and participants responded accordingly.

21.2. Results

21.2.1. Data Analysis

Results are based on median RT and accuracy (% correct) measures. In all analyses including the load condition, performance measures are based on trials in which the load task was responded to correctly. Accuracy data for the load task are presented in Appendix L. As in previous experiments, positive and negative probe trials were assessed separately due to the importance of the intact/re-paired probe comparison in assessment of binding. Analysis 22.2.2 assessed whether the attentional load task had an effect on binding. Finally, Analysis 22.2.3 assessed negative probe performance in order to ascertain whether the asymmetry results noted in Series 1 were replicated. Descriptive statistics for the probe task are available in Appendix M.

21.2.2. Is Binding Attentionally Demanding?

The following analysis was designed to assess whether the load task had any detrimental effect on binding through the comparison of intact and re-paired probe conditions (as a function of lag) in the load and no load conditions.

Reaction Time. A 2 (intact vs. re-paired probe) x 4 (lag) x 2 (load vs. no load) ANOVA for repeated measures on RT data, with load as a between-subjects factor, indicated no significant main effect of load, F(1, 77) < 1 (no-load condition: M = 822.33, SE = 37.32; load condition: M = 809.84, SE = 32.91); a significant main effect of binding, F(1, 77) = 23.87, MSE = 9348.36, p < .001; and a significant main effect of lag, F(3, 231) = 9.68, MSE =26552.10, p < .001, characterised by a significant linear trend, F(1, 77) = 19.62, MSE =35401.73, p < .001. Additionally, there was no interaction between lag and binding, F(3, 231) =1.63, MSE = 7623.99, p = .18; a significant interaction between lag and load, F(3, 231) =2.75, MSE = 26552.10, p < .05; and critically, a significant interaction between binding and load, F(1, 77) = 4.91, MSE = 9348.31, p < .05. The three-way interaction between lag, load,

and binding was non-significant, F(3, 231) < 1. Positive probe RT measures are presented in Figure 24 (A & B) as a function of lag in the no-load and load conditions, respectively.

Contrasts assessed the significant interaction between lag and load, and indicated no significant effect of load on performance at the 250ms interval, F(1, 77) = .87, MSE = 38239.55, p = .35; no significant effect of load on performance at the 500ms interval, F(1, 77) = .02, MSE = 32257.06, p = .88; no effect of load at the 2000ms lag interval, F(1, 77) = .20, MSE = 49472.36, p = .66, and finally, no effect of load on performance at the 4000ms interval, F(1, 77) = 1.20, MSE = 65101.81, p = .28. The cause of the interaction between lag and load therefore remains unclear, but is most likely an artefact of the differential pattern of performance across lag intervals, which were not picked up by this analysis.

Contrasts further examined the significant interaction between load and binding. The data indicated a significant binding effect in the control condition, F(1, 39) = 19.64, MSE = 3038.95, p < .001, and a significant binding effect in the load condition, F(1, 38) = 5.09, MSE = 1616.76, p < .05. While the binding effect was significant in each condition, effect size computations indicated a coefficient of d = .26 (a small effect) in the control condition, and d = .12 (a negligible effect) in the load condition.

Accuracy. A 2 (intact vs. re-paired probe) x 4 (lag) x 2 (load vs. no load) ANOVA for repeated measures on accuracy data revealed no significant main effect of load, F(1, 77) < 1 (no-load condition: M = 70.06, SE = 2.91; load condition: M = 72.78, SE = 2.74); a significant main effect of binding, F(1, 77) = 35.27, MSE = 146.02, p < .001; and a significant main effect of lag, F(3, 231) = 29.30, MSE = 212.11, p < .001, characterised by a significant linear trend, F(1, 77) = 59.35, MSE = 252.79, p < .001, a significant quadratic trend, F(1, 77) = 13.25, MSE = 224.58, p < .001, and a significant cubic trend, F.(1, 77) = 4.19, MSE = 158.96, p < .05. Additionally, there was no significant interaction between lag and binding, F(3, 231) < 1, and finally, no three way interaction between factors, F(3, 231) < 1. Effect size computations (Cohen's d) indicated the overall binding effect for accuracy measures was medium in magnitude, d = .41. The data are illustrated in Figure 24 (panel C: no load condition; panel D: load condition).



Figure 24. Experiment 4 - The binding effect. Panel A: RT measures in the no-load condition, depicting a significant binding effect (p < .05); a significant main effect of lag (p < .05), and no interaction between factors, p > .05. Panel B: RT measures in the load condition indicating a significant main effect of binding (p < .05), no significant main effect of lag (p > .05) and no interaction between factors (p > .05). Panel C: Accuracy measures in the no-load condition characterised by a significant binding effect (p < .05); a significant main effect of lag (p > .05), and no interaction between factors (p > .05). Panel C: Accuracy measures in the no-load condition characterised by a significant binding effect (p < .05); a significant main effect of lag (p < .05), and no interaction between factors (p > .05). Panel D: Accuracy measures in the load condition depicting a significant binding effect (p < .05), a significant main effect of lag (p < .05), and finally, no interaction between factors (p > .05). Bars represent one standard error of the mean.

Summary. Analysis of accuracy measures indicated a significant binding effect, present across all lag intervals which was not modified by the attentional load. Importantly, however, there was a significant reduction in binding in the load condition relative to the no-load condition with respect to the RT measure. Finally, as noted in previous experiments, lag performance for accuracy measures was characterised by linear, quadratic and cubic trends. The source of these trends appears to be the improvement in accuracy performance between the 250ms and 500ms lag intervals and its progressive decay thereafter.

21.2.3. The Attentional Load and Performance on the Negative Probes

Reaction Time. Negative probe RT data were subjected to a 3 (negative probe) x 4 (lag) x 2 (load vs. no load) ANOVA for repeated measures. The analysis indicated no main effect of load, *F* (1, 77) < 1 (no-load condition: *M* = 755.28, *SE* = 31.51; load condition: *M* = 748.92, *SE* = 33.27); a significant main effect of Lag, *F* (3, 231) = 5.53, *MSE* = 43840.79, *p* < .01, characterised by a significant linear trend, *F* (1, 77) = 7.10, *MSE* = 52509.23, *p* < .01, and a significant quadratic trend, *F* (1, 77) = 7.89, *MSE* = 25963.37, *p* < .01. The main effect of negative probe was significant too, *F* (2, 154) = 93.48, *MSE* = 24846.15, *p* < .001. Additionally, there was no interaction between lag and condition, *F* (3, 231) < 1; no interaction between lag and condition, *F* (6, 462) = 2.36, *MSE* = 11871.22, *p* = .06, and no three-way interaction between factors, *F* (6, 462) < 1. Negative probe RT measures are presented in Figure 25. Panel A depicts negative probe RT performance in the no-load condition, and Panel B depicts negative probe RT performance in the load condition.

LSD post-hoc tests on the main effect of negative probe indicated that RTs for bothfeatures-new probes were significantly faster than for new-location and new-shape probes ps< .05; and that RTs for new-location probes were significantly faster than for new-shape probes p < .05. Effect size analyses indicated that the difference between both-features-new probes and new-location probes was small, d = .14; whereas the difference between bothfeatures-new and new-shape probes was large, d = .81.



Figure 25. Experiment 4 - Performance for negative probe trials denoting the same pattern of results as noted in Experiment 1B. Additionally, Panels C and D demonstrate the detrimental effect of the load task on new-shape probes. Panel A: RT measures for negative probes in the no-load condition. Panel B: RT measures for negative probes in the load condition. Panel C: Accuracy measures for negative probes in the no-load condition. Panel D: Accuracy measures for negative probes in the load condition. Bars represent one standard error of the mean.

Accuracy. A 3 (negative probe) x 4 (lag) x 2 (load vs. no load) ANOVA for repeated measures indicated no significant main effect of load, F(1, 77) = 1.89, MSE = 1048.67, p = .17 (no-load condition: M = 81.80, SE = 2.29; load condition: M = 78.91, SE = 2.45); a significant main effect of lag, F(3, 231) = 3.19, MSE = 159.12, p < .05, characterised by a significant quadratic trend, F(1, 77) = 7.44, MSE = 186.87, p < .01; and a significant main effect of negative probe, F(2, 154) = 1.25, MSE = 554.09, p < .001. In addition, there was a significant interaction between load and negative probe, F(6, 77) = 4.24, MSE = 554.09, p < .05; no interaction between lag and condition, F(3, 231) < 1; no interaction between lag and negative probe, F(6, 462) = 1.76, MSE = 150.89, p = .13, and no three-way interaction between factors, F(6, 462) < 1.

LSD post-hoc tests indicated that performance for both-features-new probes was significantly better than for new-location and new-shape probes, ps < .05. Finally, performance for new-location probes was significantly better than for new-shape probes, p < .05. Effect size analyses (Cohen's *d*) indicated that the difference in performance between both-features-new probes and new-location probes was medium, d = .72, whereas the difference between both-features-new and new-shape probes was very large, d = 2.21.

Contrasts were carried out in order to assess the interaction between load and negative probe. The data indicated no significant main effect of load on both-features-new probes, F(1, 77) = .001, MSE = 67.49, p = .98; no significant main effect of load on new-location probes, F(1, 77) = .75, MSE = 112.53, p = .75; but a significant detrimental effect of load on new-shape probes, F(1, 77) = 4.77, MSE = 255.31, p < .05. Negative probe accuracy measures (as a function of lag) are depicted in Panel C of Figure 25 for the no-load condition and Panel D for the load condition.

Summary. Negative probe RT measures suggested that performance was not adversely affected by the additional load task. However, accuracy measures indicated that there was a detrimental effect of load specifically in the new-shape condition. Finally, the general pattern of negative probe performance across both dependent variables mirrored those found in Series 1: superior performance for both-features-new probes relative to newlocation and new-shape probes, the former of which was superior to the latter.

22. Discussion

22.1. Summary of Findings

Experiment 4 addressed the issue of whether the binding noted in Series 1 (where both shape and location features were task-relevant) relied in part on the availability of attentional resources. The importance of addressing this issue was three-fold. Firstly, relatively automatic binding effects were noted in Series 2 where only one feature (shape) was task-relevant, while in Series 1 it was not possible to ascertain whether the binding took place automatically, via strategic processing (or both), as both features were relevant for task completion. Secondly, the results of Series 3 hinted at a contributing effect of attentional resources to binding, whereby greater attention resources allocated to a stimulus on encoding increased the strength of the bound representation. Finally, one key claim of the EB component of WM is that the binding of features should be heavily reliant on attentional resources, introducing a testable hypothesis for the investigation of the nature of bound representations. To address the issue, Experiment 4 paired the Prabhakaran et al. (2000) paradigm (as used in Experiment 1B) with an attentionally demanding secondary task –the serial retention of a string of five digits.

According to Baddeley's (2001) formulation of the EB, access to this system can only be achieved via the central executive. Therefore, feature binding taking place in the EB should be limited to the extent that attentional resources are available. While there is evidence suggesting that focussed attention may be necessary for feature binding, (e.g., Wolfe, 1999), recent investigation into visuo-spatial memory has demonstrated that not all binding requires focussed attention. For example, Allen et al. (2006) demonstrated that the binding of colour and shape stimuli could proceed in the absence of focussed attention. Note that the binding together of their stimuli constituted property binding, and as such, may have taken place in a relatively automatic manner by virtue of appearing as properties of the same object (see also the unitisation effect e.g., Asch et al., 1960; Ceraso et al., 1998; Delvenne & Bruyer, 2004). Their findings suggest that some modes of visuo-feature integration can take place in the absence of focussed attention, and may be formed outside of the control of the EB (perhaps stemming from earlier perceptual processing).

The results of Experiment 4 indicated that a mental load reduced the binding effect in

the RT measure, without eliminating it completely. Furthermore, the load appeared to have hindered the participants' ability to inhibit the familiarity signal yielded by old locations, when occupied by a new shape, as indicated by the drop in correct rejection of new-shape probes in the load condition. That binding was not eliminated by the load suggests that binding enjoyed contributions from both controlled and automatic processes. The survival of some binding under a load may also reflect the availability of some residual attentional resources (i.e., it is possible that an even more demanding load than that used in this experiment may have reduced the binding further or abolish it). This would be an interesting avenue for further research, although there would be some methodological constraints to overcome (as increasing the load would reduce performance in the load task, reducing the amount of data that could be included in the analysis of binding).

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22.2. Location Binding and the Episodic Buffer

The mixed contribution to binding of controlled and automatic processes in Experiment 4 could have important implications for the EB. One could imagine that the EB is not necessary for location binding but may function to enhance memory traces for automatically formed bound representations, perhaps recruited as a result of intention, or task strategy. That some forms of binding may recruit the EB (e.g., location binding) and others may not (e.g., property binding, Allen et al., 2006) may be a direct result of the way in which visual features are perceived. The close connection between visuo-spatial features may result in the carry over into memory of inseparable feature bonds. Alternatively, it may be the case that the EB in its present form does not offer a parsimonious account of binding in memory. A discussion of how the EB could be modified to account for this result (along with the findings in previous experiments) is presented in Section 29.

In summary, Series 4 addressed the final aim of the present thesis, in demonstrating that location binding can be modified by the availability of attentional resources. The results add to the growing body of literature suggesting that at least some kinds of visuo-spatial integration can occur automatically in WM (e.g., Allen et al., 2006), while others recruit attentional resources.

22.3. The Effectiveness of the Load Task

The load task was selected specifically to overlap with the probe task only in the extent to which attentional resources were evoked, thus the load task was verbal and serial in nature, while the probe task was visuo-spatial. Under the Working Memory Model (Baddeley & Hitch, 1974) architecture, the processing of verbal and non-verbal information is achieved in separate memory 'stores' (i.e., the phonological loop; and visuo-spatial sketchpad respectively). That the two classes of information may have been processed independently was evidenced through the verbal load task's resilience to decline as lag increased, while performance in the visuo-spatial probe task was affected by the increase in lag duration. Additionally, performance on the load task was not subject to consolidation processes, often noted in the lag data for the probe task.

However, there was substantial evidence in the data suggesting that the attentional load task was effective in diminishing attentional resources. The effects of load were specific to conditions expected to recruit attentional resources. Firstly, the load task reduced the binding effect, as predicted by the contention that integrating visual and spatial features can be enhanced by attentional resources. Secondly, the load task had a detrimental effect on performance on new-shape trials, shown consistently across experiments to be the most difficult of the three negative probe conditions. One may reasonably argue therefore that this 'difficult' probe condition was more attentionally demanding than other negative probe conditions, and therefore more adversely affected. The implication of this finding is that under attentional load conditions, the familiarity signal from the seen-before location in this condition was even more difficult to overcome when attentional resources were shared (the load condition), than when they could be dedicated to the task (the no-load condition). This would be consistent with the idea that controlled inhibitory mechanisms may be called upon to suppress a familiarity-based erroneous response. Taken together, these findings suggest that the load task was indeed successful at diminishing attentional resources.

GENERAL DISCUSSION

23. Summary

This thesis investigated how visual and spatial feature attributes can be integrated in memory, allowing us to remember which item we saw in which spatial location - a process we Much empirical research has demonstrated the relative refer to as location binding. independence of the processing of visual and spatial attributes (e.g., Darling et al., 2006; Levene & Calvanio, 1988; Logie, 1995; Luzzatti, et al., 1998), yet the issue of how the two classes of information can be integrated in memory has received relatively little empirical investigation and theoretical implementation up until recently. The present experiments were designed to add to our understanding of the integration of visual and spatial attributes in WM with an aim to meet the following key objectives pertaining to the nature of bound visuospatial representations: (1) Can binding to location be demonstrated in a recognition paradigm? (2) What are the temporal dynamics of location binding? (3) Is location binding automatic, or is it dependent on attentional resources? and (4) What are the products of location binding, whole new objects or links between features that contribute in an asymmetrical manner. What follows is a summary of findings across experiments, and how the above objectives were met.

Series 1 met the first objective through the demonstration of binding effects across two experiments, when both visual and spatial features were task-relevant. Experiment 1A demonstrated binding for RT measures when TBR items were presented sequentially. In addition, Experiment 1A highlighted a number of methodological problems associated with the sequential presentation of TBR items, particularly with regard to recency effects. These issues were addressed in Experiment 1B using simultaneously presented shapes in locations where further evidence for location binding was noted. The results of Experiment 1B were additionally informative on our second theoretical aim. Through the inclusion of a variable lag interval between the presentation of the TBR array and the probe, the results suggested that binding to location emerged relatively early (within 250ms post stimulus offset), and could be maintained in memory for at least four seconds, the longest lag interval included in that study. In addition, the results of the lag manipulation were suggestive of a period of performance

improvement between the two shortest lag intervals (250ms and 500ms), which we interpret as a period of consolidation of the TBR array (e.g., Jolicoeur & Dell'Acqua, 1998).

Additionally, both Experiments 1A and 1B included two controls to ensure that stimuli were not recoded verbally. Firstly, the shapes and locations were selected to be difficult to attribute verbal labels to (Chuah et al., 2004), and secondly, both experiments included an articulatory suppression condition – the requirement to repeat two words out loud, during the presentation of the TBR array, and through the retention interval. Results across both experiments suggested that the requirement to articulate during the probe task failed to interfere with memory for the TBR items above the general slowing of responses (Experiment 1B).

Finally, results regarding the negative probe conditions, initially included as filler trials, suggested that visual (shape) and spatial (location) attributes may contribute unequally to probe recognition. Changes in spatial location (while the shape remained consistent) between the TBR array and the probe formed a more viable cue for response than a change in shape (while location remained consistent) – the first indication that shape and location features may contribute asymmetrically to item recognition in visuo-spatial tasks. Yet the results suggested that location change was not the sole contributor to performance, through the observation that changing *both* visual and spatial features to new items significantly enhanced probe rejection above simply changing a spatial location.

Further evidence for the asymmetrical contribution of visual and spatial features to probe recognition was found in Series 2. Using the same paradigm as in Experiment 1B (Series 1) and manipulating feature relevance, the results suggested no evidence for binding when spatial locations only were task-relevant (Experiment 2B), but that binding to location occurred automatically when shapes only were task-relevant (Experiment 2A). In addition, the characteristics of the binding effect across lag intervals (RTs) were similar to those noted when both features were task-relevant (Experiment 1B) - the size of the effect was similar in magnitude, and the binding was present from the shortest lag interval, through to the longest lag interval.

Assessment of negative probe performance as a function of lag was suggestive of a performance improvement between the 250ms and 500ms lag intervals in the shape-relevant

task, but not in the location-relevant task, suggesting that the former may have required more consolidation than the latter. Indeed, participants seemed to retain bound visuo-spatial representations in shape-relevant task, but not in the location-relevant task.

The results of Series 2 therefore served to tackle our third theoretical objective in addressing the issue of whether binding to location is automatic, or whether it is fostered by task goals. Results suggested that binding to location occurred when shapes only were task-relevant (Experiment 2A), when both features were task-relevant (Experiment 1B), but not when spatial locations only were task-relevant (Experiment 2B). Additionally, the results of Series 2 were not easily compatible with the idea that the products of location bindings are entirely new objects, but rather, location binding may be described by the parallel storage of features (e.g., Wheeler & Treisman, 2002), which are linked by connections which contribute asymmetrically to the bound percept. In terms of our fourth theoretical aim therefore, the association between shape and location features appears to be asymmetrical to the extent that encoding visual identity entailed the encoding of spatial location, while the encoding of spatial location did not entail the encoding of visual identity.

The nature of the binding asymmetry was evaluated in more depth in Series 3, through the manipulation of the encoding demands of the shape features. We compared performance in a shape-relevant task (Experiment 3B) and a location-relevant task (Experiment 3C), and manipulated the encoding demands of shape features between easy and hard to remember shapes in each (shapes derived from Experiment 3A; note the criticism of the shape selection task made on page 128, that it is difficult to establish the exact basis on which the two sets of shapes differ). Guided by previous research suggesting that memory for visuo-spatial features may be hierarchical (i.e., that the encoding of spatial location must occur prior to the encoding of object identity: e.g., Jiang et al., 2000), we hypothesised that increasing the amount of attention necessary for encoding shape features would increase the degree to which spatial locations were also encoded, by virtue of the fact that spatial location must be encoded first. Thus increasing the attention allocated to encoding shape feature would also increase the attention allocated to the location feature, enhancing the binding effect. Conversely, the relative encoding demands of shape features would not affect performance when locations only were attended (Experiment 3C) as, under the hierarchical

encoding account, location features can be encoded in isolation of the visual features occupying them. In short, we predicted significant binding effects in the shape-relevant task which varied with shape difficulty, but no significant binding effect in the location-relevant task, regardless of shape difficulty.

As predicted by the hierarchical formulation, the results indicated that when shapes only were task-relevant (Experiment 3B) location binding occurred automatically regardless of the difficulty of the shape features (RT measures). Additionally, accuracy measures suggested that binding was mediated by the difficulty of the shape features, suggesting that more attention allocated to encoding a visual stimulus, the greater the binding of stimulus features. Conversely, in the location-relevant task (Experiment 3C) no evidence of binding to location was noted in either the easy or hard shape conditions.

That there was more binding in the hard shape condition than the easy shape condition (in the shape-relevant task; Experiment 3B) suggested that attentional resources may mediate the strength of the binding which ensues. Under the hierarchical account of binding, this may be explained by the notion that spatial location had to be attended prior to the shape features, and that the amount of attention necessary to encode the shape features would be shared by the location feature, thus both features benefited. However, this supposition was limited to the extent that the results in Experiment 3C were somewhat counterintuitive. In that task, when spatial locations were attended, positive probe performance (accuracy) in the hard shape condition was superior to that in the easy shape condition. The reason for this discrepancy remains unclear. Importantly, however, as there was no evidence for binding between the two features (i.e., there was no intact/re-paired differences), the main conclusions from that study were not compromised.

The contribution of attentional resources to location binding was directly investigated in Series 4. In Experiment 4, we paired the paradigm used in Experiment 1B (Series 1) with an attentionally demanding secondary task – the retention of a string of five digits, in serial order. The results indicated that under this load condition, location binding was significantly reduced for RT measures, yet not eradicated. For simplicity, each of the key findings is discussed separately below.

24. Visuo-spatial Feature Binding in WM

The results of this series of experiments indicate that visual and spatial features may be integrated in memory, supporting the contention that visuo-spatial information may be chunked, providing some processing efficiency within the cognitive system. However, the results further suggested that the binding which takes place between visual and spatial features is restricted to specific circumstances: the binding of shapes to locations may occur when *both* shapes and locations are task-relevant; when shapes only are task-relevant; but not when spatial location only is task-relevant – providing evidence for an asymmetry in association of visual and spatial features. This will be discussed in more detail in Section 25.

Nevertheless, the finding that visuo-spatial features may be integrated in memory is consistent with recent research on binding in VSWM. For example, Luck and Vogel (1997; Vogel et al., 2001) demonstrated that memory capacity for retaining visuo-spatial items was not affected by the number of constituent features comprising those items, implying that the capacity of WM is limited only by the number of items present in a TBR array, and not the number of features. Subsequent research, however, has failed to support the fact that all features can be integrated in memory. For example, evidence suggests that VSWM cannot readily integrate features from the same dimension (e.g., Delvenne & Bruyer, 2004; Olson & Jiang, 2002; Wheeler & Treisman, 2002; Xu & Potter, 1999; Xu, 2002b), spurring the suggestion of parallel storage in WM (Wheeler & Treisman, 2002). The parallel storage account supposes that increased memory capacity noted in binding studies may be due to features from different dimensions being stored in parallel, mediated by distinct capacity limited resource pools. Wheeler and Treisman (2002) further noted that the binding between features from different dimensions could be maintained in memory by the formation links between features, but that these links are subject to available attentional resources (c.f., Allen et al., 2006, and Section 26 where the issue of the contribution of attentional resources to feature binding will be discussed in more detail).

The results presented herein are supportive of the contention that features from different dimensions can be adequately integrated in memory. Across experiments, the measure of binding was taken as a processing advantage of intact probes over re-paired probes. Intact probes represented a shape in location as presented in the TBR array, while

re-paired probes represented a shape and location seen in the TBR array, but that were initially not seen together. Both probe types contained the same information at the featural level (i.e., a seen before shape and a seen before location) and differed only in the extent to which features were initially presented as part of the same object. Thus the decrement in performance for re-paired probes relative to intact probes may have represented some decomposition cost in addressing features separately to find a match in memory to the probe.

Numerous authors have also found evidence suggesting that perceiving features as belonging to the same object can enhance later recognition for those objects. For example, Olson and Jiang (2002) noted that capacity limitations in WM pertain to both the number of simple features, but can also be limited by the number of objects irrespective of the number of features, provided that those features are perceived as belonging to that object. The integration of visuo-spatial features may therefore be fostered by the way in which perceptual mechanisms process items (e.g., Ceraso et al., 1998; Delvenne & Bruyer, 2004; Walker & Cuthbert, 1998). In our experiments, on any given trial (except for in Experiment 1A) there were six task-relevant features simultaneously available for encoding (three shapes, and three spatial locations), yet across experiments, evidence suggested that probes were best recognised when they represented an 'object' seen before in the TBR array, as opposed to when they comprised features that initially made up separate objects (although this benefit was restricted to circumstances where both features were attended, or shapes only were attended). The finding can be related to the concept of perceptual unitisation, proposed in the visual perception literature (e.g., Asch et al., 1960). Perceptual unitisation suggests that 'object-hood' occurs as a result of direct links formed between features of an object, such that the later retrieval of one feature results in the retrieval of all features. However, while the present results are consistent with the claim that perceptual unitisation can aid in feature integration, our results are not consistent with the idea that the links formed between visual and spatial features are reciprocal. Rather, the results suggest that bindings between visual and spatial features are formed in a relatively automatic fashion when shapes are taskrelevant, but not when locations are task-relevant (see Section 26).

Our results are further consistent with the idea that features are readily integrated when verbal labelling is precluded. For example, Walker and Cuthbert (1998) suggested that

visual memory supports feature associations primarily while features are perceived to belong to the same object, in the absence of verbal recoding, which is assumed to be able to support between-object associations. In Experiments 1A and 1B of the present report, articulatory suppression failed to impact on visuo-spatial binding. The following section addresses the asymmetrical relationship between visuo-spatial features.

25. Hierarchical Processing and the Binding Asymmetry

One issue that is pivotal to our understanding of visuo-spatial feature binding is that of the nature of bound representations. For example, does binding to location result in links between all features where retrieval of one feature results in retrieval of all features? Or do bound representations consist of new mental objects maintained independently of their constituent features? As touched upon above, the results of the present study suggest that the binding of shapes to locations does not fit with the idea of the formation of a whole new object representation in memory, but rather, is more consistent with the idea that features are stored in parallel, but linked (or bound) in memory through asymmetrical connections (Series 2; Series 3). Binding may occur automatically when shapes only are task-relevant, but not when spatial locations are task-relevant.

Our results are consistent with the idea that full integration is not, by necessity, the mode of storage in visuo-spatial tasks. Similar evidence has been noted in the memory literature. For example, Jiang et al. (2000; see also Finke et al., 2005; Olson & Marshuetz, 2005) noted that the encoding of item identity in their studies was automatically accompanied by the encoding of spatial location while the reverse was not true. Jiang et al. (2000) argued that VSWM may be organised in a hierarchical manner. When a visual image is encountered, a spatial configuration of items in the TBR array is formed relatively automatically. Subsequently, the features comprising the configuration are bound to the respective parts of that configuration.

The results of Series 2 and 3 can be readily reconciled under this account. In the shape-relevant tasks, analysis of the spatial layout of TBR items would take place first, resulting in an automatically formed configural representation of those items. Only then could the identities of items appearing in that configuration be assessed. In short, the processing of item identity cannot proceed without some reference to spatial location, explaining why the features under these circumstances were integrated. Conversely, in the location-relevant task, analysis of the TBR array could stop at the spatial configuration stage, as this information would be sufficient to complete the task – there would be no need to assess the shapes under these circumstances, explaining why no binding of spatial location to object identity took place. Further support for this claim was gained through the observation that

(numerically) reaction times were faster in the location-relevant tasks (Experiments 2B and 3C) relative to the shape-relevant tasks (Experiments 2A and 3B). A post-hoc independent samples t-test indicated that this difference was significant, t (38) = 2.30, p < .05 (shape task: M = 807.88, SE = 30.05; location task: M = 688.26, SE = 42.34, SE = 42.34).

Additional support for the hierarchical encoding account was noted in Series 3, where the difficulty of encoding shape features was manipulated. The hierarchical encoding account suggests that spatial location and object identity are linked via the necessity to derive the spatial layout of items prior to the identity of what occupies them. Thus, when a shape is encoded, the spatial location is encoded (and integrated) automatically. It was hypothesised that in increasing the amount of encoding necessary for processing shape features, the spatial location feature would also benefit from the additional resources, by virtue of its close connection to the shape feature. This is indeed what was found. Results from Experiment 3B suggested more of a binding effect for a hard shape set relative to an easy shape set for RT measures. Conversely, in the location-relevant task (Experiment 3C), manipulating the difficulty of the (irrelevant) shape features did not affect performance – there was no evidence for binding for either of our measures. Processing seemed to stop at the spatial configuration stage.

The term 'configuration', in this context, relates to how spatially distributed items are encoded in relation to one another (relative spatial location), rather than retaining each item in isolation (absolute spatial location). The latter is defined as a change in location between the TBR array and the probe, and the former, a change in location which alters the position of the target item relative to some frame of reference (Olson & Marshuetz, 2005). Olson and Marshuetz (2005) directly assessed the type of spatial representation (relative or absolute) that becomes automatically associated with item identity. Their results suggested that relative spatial location may be critical, consistent with Jiang et al.'s (2000) claim for the formation of a spatial configuration.

With regard to the type of spatial representation that was encoded automatically in Series 2 and 3, our results are less clear. Across experiments, a single probe item was used, disrupting the initial configuration of items. However, since the TBR array was presented within a frame, as was the probe item, one suggestion is that relative spatial location may

have been important – items may have been encoded with the frame serving as a 'frame of reference'.

In sum, evidence suggests that VSWM may be organised hierarchically, such that a simple array-based configuration of items precedes the analysis of what occupies those locations. The binding asymmetry noted in Series 2 and 3 may therefore be a general characteristic of visuo-spatial memory. Indeed, we have already seen that a binding asymmetry occurs with stimuli other than those used in our experiments (Jiang et al., 2000: colours in locations; Olson & Marshuetz, 2005: simplified faces in locations).

Further evidence from divergent areas of research indicates that the asymmetrical relationship between visual and spatial attributes may extend across different levels of processing, suggesting that the asymmetry may be a characteristic of visuo-spatial cognition universally. For example, in visual attentional selection, several lines of research have demonstrated that spatial location plays a special role. Object-based selection does not occur in a space invariant way (e.g., Kim & Cave, 2001). Further, evidence suggested that spatial attention is deployed even when irrelevant for task completion (e.g., Lamy & Tsal, 2000; Hoffman & Nelson, 1981; Kim & Cave, 1995); and that errors in tasks tapping selection for features other than spatial location are often spatial in nature, even when space is irrelevant for task completion (e.g., Tsal & Lamy, 2000). Additionally, in perceptual integration, the formation of object-files is thought to be dependent on attendance to spatial locations (e.g., Allport et al., 1985; Hommel, 1998; Kahneman et al., 1992; Treisman, 1993).

One explanatory model of feature binding at the perceptual level is the Feature Integration Theory (FIT: Treisman & Gelade, 1980; Treisman, 1998), which encompasses the idea of the critical importance of spatial location for feature integration. According to the model, features are initially registered independently, each feature type within its own feature map. Spatial location is represented in a master map of locations, which represents regions of space without the features occupying them. Integration takes place through the feature maps signalling whether a particular feature is present in the visual field, and then the master map of locations is scanned by a scalable window of attention, which checks for currently active features within the feature maps, within a particular location. Tasks which do not require integration can be solved by checking the feature maps for flags signalling the

presence of that feature, and do not require attention. Conversely, correctly associating a combination of visual features requires serially applied focussed attention and the retrieval of connections between the feature maps and the master map of locations (e.g., Cohen & Rafal, 1991; Treisman & Schmidt, 1982; Treisman & Gelade, 1980). According to Treisman (1993), spatial location may form the 'glue' holding features together. The binding asymmetry observed in Series 2 and 3 are compatible with FIT. The location-relevant task could be solved by checking the master map of locations. Conversely, solving the shape-relevant task may require retrieval of connections between the features maps and the master map of locations.

Interestingly, a recent investigation of verbal-spatial binding by Clissa, Maybery, Fox and Parmentier (2007) found evidence for an asymmetry in the association between verbal and spatial features in the direction opposite to that noted in the present studies. Using a paradigm based on Prabhakaran et al. (2000), but presenting verbal sounds from loud speakers, evidence from negative probes (negative identity; negative spatial and negative composite, analogous to the new-shape, new-location, and both-features-new probes respectively) suggested that sound identity played a greater role in binding than spatial location, in contrast with what was observed in the present thesis. The implication of this finding is that spatial location seems to be prominent in the visual domain, but not in the auditory verbal domain (see Kubovy & Van Valkenburg, 2001). How the asymmetry finding may be theoretically implemented is discussed in Section 29. The following section discusses the relationship between binding and attentional resources.

26. Binding and Attentional Resources

The issue of the contribution of attentional resources to binding in memory is of pivotal theoretical importance, particularly with regard to the newly proposed episodic buffer component of the Working Memory Model (e.g., Baddeley, 2000), under which a key role for attentional resources is stipulated. More generally, the question of the contribution of attentional resources to feature integration is related to the issue of whether visuo-spatial feature binding occurs in an *automatic* or *controlled* fashion. Automatic feature integration would take place without intent on the part of the perceiver, whereas controlled feature integration may be driven by task goals, strategy or intent. Importantly, the latter but not the former would be reliant on attentional resources.

In terms of the memory literature, experimentation to date indicates mixed results as to the necessity of attentional resources for binding. For example, while some authors have found evidence that memorial binding is dependent on attentional resources (e.g., Wolf, 1999; Stefurak & Boynton, 1986; Wheeler & Treisman, 2002), others have failed to find such a dependence (e.g., Allen et al., 2006). Additionally, the involvement of attentional resources in feature integration has been supported by neuropsychological research, which suggests that the prefrontal cortex is recruited by the CE component of the working memory model (e.g., Baddeley, 1986) but also for feature integration (e.g., Prabhakaran et al., 2000; Simon-Thomas et al., 2003).

Compelling evidence against the essential role for attention to binding was reported by Allen et al. (2006) who failed to find any detrimental effect of a variety of attentionally demanding concurrent tasks on the integration of their colour and shape stimuli above and beyond those noted for individual features. Recall that in the memory binding literature *property* binding had an integration advantage over *part* binding (Xu, 2002a; 2002b). Allen et al.'s (2006) stimuli involved property binding by virtue of the fact that the colour of an item (or shape) is a property of that shape. The binding of their stimuli may therefore have occurred automatically as a result of features comprising properties of the same object.

The results from Series 2 and 3 suggest that binding to location may occur automatically when shapes are attended, but not when locations are attended. In Series 3, however, additional evidence suggested that binding to location (when shapes only were

task-relevant) may have been enhanced through the attentional resources afforded by a visual stimulus. The assertion was made through the observation that harder to encode visual features led to larger binding effects than stimuli which were functionally easier to encode.

As discussed above, the binding noted in Series 2 and 3 was thought to reflect the automatic nature of binding, as integrating visual and spatial features in those studies was not a strategy which would aid performance. However, the binding noted in Series 1, where both features were attended may well have benefited from attentional resources. In each experiment, participants had the task of maintaining 6 individual features (3 shapes and 3 spatial locations). Although task instructions – to indicate whether a probe represented a shape and location seen before in the TBR array *irrespective* of whether they were initially presented together - did not explicitly encourage binding, participants may have bound features as a strategy to reduce the total number of 'items' to be retained (e.g., Luck & Vogel, 1997).

Series 4 addressed the issue of whether binding to location (when both features were attended) was indeed an automatic process, or whether it recruited additional attentional resources. Our results demonstrated that the binding of shape to location was significantly reduced (yet not eradicated) in a task where both features were attended and an attentional load task was employed (the retention of a string of five digits in serial order). The load task was selected to be verbal in nature so that any interference taking place between memory for items in the TBR array, and the string of digits were due to the overlapping attentional requirements of each task, as opposed to tasks interfering with one another on the basis of competition within the same memory store (e.g., Baddeley & Hitch, 1974). Series 1 demonstrated that the need to articulate during the probe task failed to have an effect on performance strengthening the claim that the disruption to binding noted in Series 4 was due to the attentional demands of the secondary task, as opposed to the sub-vocalisation of the digits in the string. Additional support for the contention that both tasks overlapped only to the extent that they relied on attentional resources was evidenced through reduced performance to new-shape probes in that task, under load conditions. Across experiments, the new-shape condition was repeatedly demonstrated to represent the 'hardest' of the negative probe

conditions, and thus may have recruited more attentional resources. The load task therefore interfered not only with performance in terms of binding, but also on this harder negative probe condition.

That the binding effect was significantly reduced under a concurrent cognitive load in Series 4 suggests that attentional resources may enhance the binding taking place between shape and location features – a finding which would not be expected if binding in those studies was taking place in a solely automatic manner. Thus location binding may benefit from a contribution of automatic and effortful processes. Indeed, there may not be a strict dichotomy between automatic and effortful binding, but rather the two may represent different ends of a continuum. The attentional contribution to binding may simply depend on the amount of resources that are available. Further research should vary systematically the attentional demand imposed by a secondary task to establish whether or not the binding thought to be underpinned by relatively automatic processes can disappear in some circumstances.

In sum, our results suggest that location binding may occur automatically when shapes are task-relevant (e.g., Series 2 and 3), but may be enhanced by attentional resources (Series 4). How this finding, along with the binding asymmetry findings may be implemented theoretically forms the basis of Section 29. The following section discusses the observation of a period of consolidation in memory for the TBR array.

27. Consolidation of the To-Be-Remembered Array

The results of the present series of experiments were indicative of the fact that visually presented stimuli may be subject to a consolidation process in memory. The term 'consolidation' refers to how information initially encoded in great detail in sensory memory is transferred into short-term memory, such that it can remain in the absence of bottom up feed (e.g., Jolicoeur & Dell'Acqua, 1998).

That consolidation processes may be at play was a supposition made through the observation that probe recognition over the four lag intervals was often accompanied by performance improvement between the 250ms and 500ms lag intervals. The result is consistent with previous experimentation. For example, Jolicoeur and Dell'Aqua (1998) presented two concurrent tasks to participants. One involved the retention of visual stimuli, and the other requiring a speeded response to an auditory presented tone, which occurred at various SOAs. Their findings suggested that response times to the tone were slower at shorter SOAs than at longer SOAs, suggesting that the consolidation of the TBR items interfered with participants' ability to respond to the tone. The authors argued that the consolidation of visuo-spatial stimuli requires central attentional mechanisms. Converging evidence is provided by Jiang (2004) who noted that the period of consolidation of TBR items takes 200-500ms post stimulus offset, a suggestion which fits well with the time-scale observed in the present studies.

However, in Experiment 4 of the present thesis, sharing attentional resources between the probe task and the load task did not modify the consolidation effect. An interaction may have been too small to be detected or, alternatively, the attentionally demanding secondary task adopted (the retention of a string of digits in serial order) may not have been demanding enough to yield such effects. Jolicoeur and Dell'Aqua (1998) further found evidence that the period of consolidation increased with TBR workload. In line with this finding, the period of consolidation observed varied with the type of information to be encoded in Series 2. Specifically, performance for negative probes in the shape-relevant task (Experiment 2A) was characterised by a period of performance improvement between the 250ms and 500ms lag intervals, whereas negative probe performance in the location-relevant task (Experiment 2B) was characterised by an absence of such performance improvement.

The finding suggests that the nature of material encoded in the two tasks differed, such that the encoding of shapes required more processing than the encoding of spatial location. Additionally, results from positive probes (our measure of binding) suggested that participants retained bound visuo-spatial information in the shape-relevant task, but not in the location-relevant task, and may therefore have required more consolidation than the encoding of spatial location.

Although the investigation of consolidation processes was not an aim of the present series of experiments, our results reinforce the usefulness of including a variable lag interval between the presentation of the TBR array and the probe in recognition tasks. This is discussed in more detail below.

28. The Durability of Bound Visuo-Spatial Representations

One key aim of the present series of experiments was to try to ascertain the temporal dynamics of bound representations. The utility of manipulating the lag interval between the TBR array and the probe has already been discussed above in terms of the consolidation of TBR items – an incidental finding which nevertheless was informative on the nature of the maintenance of visuo-spatial representations. Additionally, however, varying the interval between the lag and the probe is pivotal in establishing the time course of bound representations. Previous research into binding in WM has typically only included a fixed delay interval, providing findings which may represent one 'still-frame' of a dynamic process. In the context of the present series of studies, the variable lag interval was included in order to try to ascertain whether binding to location takes time to emerge, whether it is short lived, or both.

Across experiments (with the exception of Experiment 1A), when binding occurred it was present (for at least one dependent variable) from the shortest lag interval through to the longest lag interval, suggesting that binding to location may occur relatively quickly, and can be maintained in memory for a minimum of 4 s. However, that the binding of visuo-spatial representations was present at the shortest lag (250ms) does not mean that binding occurs within 250ms, because TBR items were onscreen for 2000ms prior to the onset of the lag interval, potentially increasing the amount of time during which bindings emerged. As discussed above, the lag data were suggestive of a period of consolidation of TBR items, indicating that once TBR items were no longer in view the array representation had to be consolidated into a viable memory representation. That the binding (an intact over re-paired probe advantage) was already present at the shortest lag interval (250ms) suggests that binding may have already taken place by this time. Future research should investigate in more depth the speed during which bound representations are created by manipulating shorter lag intervals, and the duration for which TBR items are present on screen.

While there is little research in the memory domain on the time-course of bound visuo-spatial representations, investigation in the field of perceptual integration has provided results consistent with those noted here. Recall that an object-file is defined as a fully integrated episodic representation of a currently attended object (e.g., Kahneman et al., 1992;

Treisman, 1993). Using different methodologies, evidence from perceptual binding studies suggests that object-files can persist for around 4 seconds when the object is no longer in view (Hommel, 2002). That the representation persisted in the absence of bottom-up feed suggests that perceptually integrated objects can be maintained in memory for a duration similar to that noted in our experiments.

The data presented herein suggested that the binding effect across lag appeared to be most robust when *both* features were task-relevant (Experiment 1B: binding present for both DVs), relative to when only shapes were task-relevant (e.g., Experiment 2A: binding present only for RT measures across all lag intervals). This finding further supports the claim that the strength of the binding may depend on the amount of attentional resources allocated to the completion of the task. When both features were task-relevant, participants may have allocated more attentional resources to the maintenance of both the visual and the spatial attributes, and additionally may have adopted strategic processes (perhaps in order to reduce the overall memory load from 6 to 3 items) As a result the binding may have endured for longer. However, the results of Series 2 and 3, where either shapes or locations were attended may have reflected more automatic binding (resources allocated to encoding the shapes only), resulting in the binding effect over lag being less robust. Nevertheless, regardless of the possible contributions of strategy to binding, the affect of lag was similar across all experiments.

29. Location Binding: Theoretical Implementation

How might feature binding mechanisms operate within memory? The present section discusses how the cohort of findings from the present series of experiments may be implemented theoretically. The section begins by discussing how the present findings may be implemented within existing theoretical constructs, and culminates in some speculation as to how the binding mechanism may operate in memory.

The EB component of the WM model was proposed in order to account for evidence suggesting that information originally assumed to be processed independently can be integrated in WM. The buffer is assumed to be a temporary storage system for integrated information originating either from the slave systems of the WM model (e.g., the phonological loop, and the VSSP) or long term memory. The EB is assumed to be under the control of the CE, which retrieves disparately processed featural information through focussed attention. As such, the buffer is limited in the extent to which CE resources are available (Baddeley, 2001). Two key findings of the present series of experiments have implications for the EB formulation. Firstly, the observation that the integration of visual and spatial features may be reduced when attentional resources are shared between two tasks (Series 4); and secondly, that binding to location is represented by links which are asymmetrical in nature (Series 2 and 3).

The finding in Series 4 that location binding was reduced when an attentional load task was employed suggests that, consistent with the model, the availability of attentional resources can contribute to location binding. However, as the binding was significantly reduced, yet not eradicated under load conditions for RT measures, and no reduction in binding was present for accuracy measures, the results additionally suggest that at least some binding to location may have taken place automatically when both features were attended. Additionally, Series 2 and 3 demonstrated the automaticity of binding (when shapes were attended). The EB may therefore function to enhance memory traces for automatically formed bound representations as a result of task strategy or intent to bind (e.g., when both features are attended, to reduce to total memory load). Indeed, the results of Allen et al. (2006) suggest that visuo-spatial feature binding may constitute a class of binding that does not, by necessity, recruit the EB, perhaps as a result of perceptual unitisation (e.g., Asch

et al., 1960; Ceraso et al., 1998; Delvenne & Bruyer, 2004).

More broadly than studies using visuo-spatial stimuli, findings from other areas of research call into question the necessity of attentional resources for binding. For example, investigations of memory for paired (word) associates have adopted a paradigm for assessing cognitive change with aging which measures whether dividing attention in younger adults can mimic binding deficits typically displayed by older adults (e.g., Cowan, Naveh-Benjamin, Kilb & Saults, 2006; Naveh-Benjamin, 2000; Naveh-Benjamin, Guez, Kilb & Reedy, 2004; Naveh-Benjamin, Guez & Shulman, 2004; Naveh-Benjamin, Hussain, Guez & Bar-On, 2003). The paradigm involves contrasting memory performance for items with memory performance for associations between items. Overwhelmingly, results using this type of procedure indicate that memory performance for younger adults under divided attention conditions does not mimic the pattern of deficit displayed by older adults. In fact, dividing attention in younger adults had an equal effect on both associative memory and memory for individual items.

Given the accumulating evidence that binding between features can take place in the absence of focussed attention, one important unresolved issue is where the automatically formed bound representations would be created within the working memory model. In terms of visuo-spatial memory, Allen et al. (2006) suggested that the visuo-spatial subsystem might support initial feature integration in an automatic manner, without recruiting executive processes (or the EB). That the VSSP of the working memory model might be equipped to deal with visuo-spatial feature integration is an interesting contention. However, research suggesting a fractionation of the VSSP into separable visual and spatial modules presents something of a paradox (e.g., Della Sala et al., 1999; Farah et al., 1988; Logie, 1995; Logie & Pearson, 1997). If visual and spatial features are indeed stored independently in the visual cache and inner scribe (Logie, 1995), respectively, and the binding of these features does not recruit an additional memory buffer, the question still remains as to how these features are integrated in memory.

One proposal is to stipulate an additional buffer inside the VSSP, the function of which would solely be to integrate visual and spatial material. In addition sub-buffers would need to be implemented within the phonological loop, in order to account for how paired word associates can be integrated in the absence of focussed attention. Additionally, each buffer

would need to be interfaced with long-term memory in order to provide support for semantic content etcetera. In short, the supposition is difficult to test empirically. Alternatively, the episodic buffer's close reliance on central executive resources could be amended by stipulating additional direct connections between the VSSP and the episodic buffer. This would allow the buffer to deal with both automatic and more attentionally demanding binding in memory. However in this case the episodic buffer would account for any type of binding and would therefore not be particularly useful as a concept to examine the potential distinctions between different binding processes.

Independently of the way that WM model may be amended to account for the mixed controlled and automatic nature of binding, there is at least one further reason to reject a buffer view of binding: the asymmetry in association between visual and spatial features (see also Jiang et al., 2000; Olson & Marshuetz, 2005). That features may not contribute symmetrically to feature binding is a particularly difficult parameter to implement into any construct seeking to explain binding through stipulating the creation in memory of an entirely new object. How can binding take place during attendance to one feature, but not to another? Further, how can one feature influence recognition more than another if the two features have been merged into one new construct? Feature binding as envisaged by Allen et al. (2006) in the first systematic investigation of the EB for visuo-spatial stimuli implies that perhaps asymmetrical relationships between features have not yet been considered: "For any type of chunk to be useful, its constituents must be sufficiently well bound as to allow the retrieval of one component to evoke the remainder" (Allen et al., 2006, p.1).

There are three ways to reconcile this finding under the WM formulation. Firstly, it might be that some bound representations get obligatory (and automatic) access to the episodic buffer, while other representations are handled in parallel (for example, by the respective components of the VSSP, for visual and spatial stimuli). This idea is underpinned by the notion that feature information is stored both in a fragmented fashion (e.g., in the respective parts of the VSSP, consistent with research demonstrating the independence of the two streams of information; for example with brain damaged patients: Farah et al., 1988; Luzzatti et al., 1998; in selective interference experiments: Della Sala et al., 1999; and in developmental research: Logie & Pearson, 1997) and also in the buffer, as an entire new
entity, but is limited by the availability of resources within the system. However, the representation of object features more than once in memory does not seem to be a particularly efficient way to approach the problem. Secondly, the buffer may be amended so that it is not viewed as a store, per se, but rather it functions as a pointer between independently stored features, indicating which features belong together. In this sense the buffer could be converted to a 'linker' rather than a memory store for bound representations. Finally, the solution may lie in a combination of the above suppositions. It may be that while two visual features (e.g., colour and shape, Allen et al., 2006) are bound into 'object' representations in a relatively automatic manner (e.g., outside of the episodic buffer), spatial location may not form part of a visual 'object' at all. Under this interpretation spatial location is not another simple visual feature to be bound, but rather it serves to index *bound* visual features. Thus while the binding of two visual features may result in the creation of a new object structure, the binding of this integrated object to location may be characterised by asymmetrical links between the visual and the spatial, the latter but not the former of which recruits the episodic buffer and attentional resources.

One key argument for assuming a buffer for integrated information came from the brain imaging study of Prabhakaran et al. (2000) who demonstrated specific activation in the frontal cortex during the maintenance of bound representations, establishing neural correlates for a potential store for bound representations. However, Ruchkin et al. (2003) argued that such activation may result from keeping links between features in an active state. A view of binding building on this type of assumption is presented below. In short, as the EB is a relatively young construct and its functional characteristics are yet to be fully specified, it is not possible to draw any firm conclusions with regard to the binding asymmetry in terms of that model. In order to be able to adequately account for findings such as ours, any construct seeking to explain visuo-spatial feature binding should include the following assumptions: 1) a hierarchy of stages of processing in VSWM; 2) that some visuo-spatial features can be integrated automatically, perhaps as a result of perceptual object-hood.

From the evidence presented herein, we speculatively propose that features to be integrated are stored in parallel in memory, and that these features are bound together by links between features which indicate which features go together, consistent with the

supposition of Wheeler and Treisman (2002). In addition, the links can be enhanced by the availability of attentional resources, with the strength of the binding representing how much of these resources are allocated to the task, and how features are perceived.

The notion of parallel storage rather than the formation of an entire new memory percept is supported by other lines of research. For example, aging studies typically demonstrate that older participants have a deficit in associative memory compared with younger adults, even when they do not differ from younger adults in terms of item memory (e.g., Cowan, et al., 2006; Mitchell, Johnson, Raye & D'Esposito, 2000; Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2004; Naveh-Benjamin et al., 2004; Naveh-Benjamin et al., 2003). In addition, studies of schizophrenic participants indicate that memory performance decline is well described by a deficit in combining contextual cues (i.e., binding) while memory for individual events remains unaffected (e.g., Lepage, Montoya, Pelletier, Achim, Meniar & Lal, 2006; Waters, Maybery, Badcock & Michie, 2004).

Notably, in the realm of long-term memory for paired word associates, Naveh-Benjamin (2000) proposed the associative-deficit hypothesis of aging, which distinguishes between memory for single units, and memory for the associations between them (see also Gronlund & Ratcliff, 1989). The hypothesis suggests that a major factor in memory decline that accompanies old age is a deficiency in creating and retrieving links between single units of information. Interestingly, Naveh-Benjamin et al. (2003) extended this finding to associations between pairs of pictures, and further demonstrated that if the items to be associated are already linked in some way (in this experiment, via semantically related words) the older adults' associative deficit was reduced, presumably because pre-existing associations could be relied upon, rather than performance depending on the establishment of new episodic links. Therefore, the automaticity with which information is integrated (linked) may depend in part on the 'fluency' with which two features are related. For example, automatic binding in the visuo-spatial domain may be dictated by perceptual object-hood (e.g., Ceraso et al., 1998; Walker & Cuthbert, 1998; Xu, 2002a). But more broadly speaking, if two items are closely related, binding may be fostered in a relatively automatic manner.

While the above findings pertained to developmental data (e.g., the cognitive decline in older adults memory function), and come from studies typically viewed as assessing long-

term memory, is it is apparent that adequate performance involved the establishment of connections among single units. Equally, before information becomes a long-term memory construct, it presumably has to pass through working memory. Some schools of thought argue that there is no need to separate long-term and short-term memory processes at all that both can be viewed as different states of the same information (e.g., Cowan, 1999; 2001; Oberauer. 2001; 2002). Both the view of Cowan and Oberauer posit that long term memory and short term memory are not distinct memory stores, but rather, they represent different states of activation of the same representations. Similarly, with regard to feature binding in memory, Ruchkin et al. (2003) suggest that: "...neural connections underlying the binding processes that produce episodic links are the basis for both short-term and long-term episodic memory. Recall and maintenance of episodic information involves the activation of the binding circuitry; retention of novel episodic information involves the operation of binding formation and the initial consolidation process. In either case, the same neural connections are involved." Ruchkin et al. (2003; pp5). Rather than positing distinct memory stores for different classes of information, this type of proceduralist view assumes that information is 'stored' where it is initially processed. This view is particularly interesting given that the literature suggests that the binding asymmetry spans various levels of processing, from attentional selection (e.g., Hoffman & Nelson, 1981; Kim & Cave, 2001; Lamy & Tsal, 2000; Tsal & Lamy, 2000) to memorial binding (e.g., Jiang et al., 2000: Olson & Marshuetz, 2005).

One important aspect of the formulation of binding in memory presented here is that the links formed between two features are not, by necessity, reciprocal. This may be a direct result of the order of encoding of each stimulus event. For example, the hierarchical relationship between shape and location features (discussed above) dictates that spatial location must be encoded prior to the encoding of the identity of the item, conditioning the direction of the links between those features. Similar ideas to this can be found in the associationist view of psychology, where asymmetries in association are also acknowledged. For example, according to that view, the association formed between two elements is sensitive to the order in which those items were encoded (e.g., Ebbinghaus, 1885/1913). Under Rizzuto and Kahana's (2001) independent association hypothesis, if feature A and feature B are encoded in successive order, the link formed between A and B is stronger than

the backward association between B and A. Similarly, findings using free recall tasks indicate that when participants are presented with a series of items and are asked to recall them freely, forward transitions are significantly more frequent that backward transitions (Kahana, 1996), again suggesting, albeit at a different level of processing, that the order of encoding can dictate the direction of the associations formed.

The order in which successive feature events are encoded (e.g., spatial to visual, or auditory identity to spatial) may have evolved as a function of the initial importance of each signal in each modality. Recall that contrary to the findings presented herein, Clissa et al. (2007) found that identity was the prominent feature in auditory-spatial feature binding.

In practical terms, that spatial location is the critical feature in visual cognition, whereas item identity seems to be critical in the auditory domain perhaps is not a surprising finding. Objects in the visual world are located in distinct spatial locations, and affording an action towards a particular object requires maintenance of spatial location information, such that the correct item can be located. If one needed to simply retain information pertaining to where objects are, without the necessity for retaining what they are, it seems plausible that a low-level array-based representation would suffice. Binding to location under those circumstances may not be necessary at all. In terms of auditory memory, the derivation of the identity of the auditory signal may be pivotal because determining the identity of a sound is initially more important than where it is coming from. In short, asymmetries in association between visual/spatial information and auditory/verbal information may be different as the importance/dominance of each feature within each respective domain differs. Thus the cognitive system may have developed to bias the direction of integration between different feature classes in order to provide the most suitable, and most economical usage of resources. In sum, we have presented, based on the findings presented in this thesis, one speculative view of how feature integration may operate in memory. Yet this investigation constituted only an initial attempt to try to understand visuo-spatial feature integration. What follows is a summary of unresolved issues and some suggestions for future research in this area.

30. Unresolved Issues and Future Research

The findings presented in this thesis provide potentially useful constraints on the future development of mechanisms for explaining visuo-spatial feature integration, but on their own, do not allow us to draw any firm theoretical conclusions. Additional research is necessary in order to establish further the characteristics of bound visuo-spatial representations, but also for establishing a universal explanation of binding in memory.

The present series of experiments left unanswered the issue of whether the binding between shapes and locations takes place in a truly automatic way when shapes only are attended. In Series 2 and 3, as binding was not a strategy which aided performance, it was inferred that the binding under these circumstances was carried out automatically. As discussed above, there may not be a clear dichotomy between automatic and effortful binding processes, rather the two may represent different ends of a continuum. Establishing the contribution of attentional resources to binding when only one feature is attended would allow us to determine the extent to which this 'automatic' binding is actually effortless, and would allow the further stipulation within the model set out above of how and when focussed attention may be used in feature integration. Practically, this could be achieved through pairing the paradigm used in Series 2 (i.e., a task where shapes only are attended, and a task where locations only are attended) with an attentionally demanding secondary task, as used in Series 4. Additionally, the relative demands on the secondary task could be manipulated in order to establish the extent to which binding varies with available attentional resources.

Secondly, while we attempted to gain a picture of the time course of binding, our results did not allow us to delineate the complete life cycle of bound representations. Although our manipulation of the lag interval between the TBR array and the probe was useful in establishing that binding to location emerged relatively early (250ms stimulus offset), and could be maintained for at least 4 seconds, future investigation is necessary in order to (1) establish how early bound representations actually emerge, and (2) at what point bound representations break down. This could be achieved by varying more stringently the lag interval between the TBR array and the probe, and additionally by manipulating shorter lag intervals than the 250ms one used here. As pointed out above, any conclusion about how early bound representations are formed is limited by the duration for which TBR items are on-

screen prior to the onset of the lag interval. To accommodate this, future research could include the constraints outlined above, but in addition, manipulate the presentation time for TBR items.

In the speculative formulation of feature binding in memory presented above, we tentatively suggest that binding asymmetries arise between features, and that specifically, these asymmetries may arise as a result of the order of encoding of each stimulus event. The hierarchical formulation of the binding asymmetry between visual and spatial stimuli holds that spatial location is necessarily encoded prior to the encoding of object identity. In the context of the present series of studies, but more broadly in the context of binding in memory in general, future investigation could adopt brain imaging techniques (e.g., MEG) capable of mapping the temporal dynamics of processing. Appropriate techniques could isolate whether asymmetries indeed arise as a result of the temporal order of stimulus encoding but also allows testing of the accompanying assumption, that events that are encoded simultaneously (rather than in succession) may be bound by symmetrical feature links.

In addition, further experimentation could assess whether asymmetries can be noted with simple *visual* features. If this is the case, strong evidence would have been gained for the idea that binding results in the formation of links between features, rather than the creation of a new composite object structure. Conversely, if future research is unable to note asymmetries between simple visual features the evidence would support the rival hypothesis that while visual features are integrated into object representations, spatial location does not form part of that object. Thus binding to location may be underpinned by a separate mechanism to binding between visual features, which is characterised by asymmetry.

Finally, it has become apparent that processes involved in binding within short-term memory tasks may mirror those observed in long-term memory tasks. Indeed, according to some, the two concepts may be indistinguishable (e.g., Ruchkin et al., 2003). Thus, our finding of asymmetrical feature links may be informative on models seeking to explain memory deficits which manifest in specific populations (e.g., aging: e.g., Cowan et al., 2006; Mitchell et al., 2000; Naveh-Benjamin, 2000) to provide a generalised model. For example, in aging it might extend Naveh-Benjamin's (2000) associative deficit hypothesis. More practically, the observation that attendance to one feature can result in the spontaneous

binding of another feature has key implications for the creation of paradigms seeking to examine binding, not only within these populations but in general. Tasks specifically wishing to assess memory for visual and spatial memory independently should be created with the asymmetry in mind in order to avoid overlap in processes which may distort results (i.e., what appears to be a test of shape memory may in practice be an assessment of the binding of shapes to locations).

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APPENDICES

Appendix A (1)

Itinerary of 16 shapes used in Series 1, Series 2 and Series 4 (not to scale).

































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Appendix A (2)

Map of locations used in all experiments (not to scale).



Appendix B

Analysing the Prabhakaran et al. (2000) paradigm using the signal detection method.

Results across experiments were also analysed using signal detection theory, after Macmillan and Creelman (1991). However, as the d-prime measure yielded the same pattern of results as the simple accuracy measure, we decided to adhere to the most readily interpretable method (accuracy as % correct). What follows is a description of how the Prabhakaran et al. (2000) paradigm may be analysed using the signal detection method.

D-prime where both features are attended.

Calculating d' For Positive Probes. The calculation of d' for positive (intact and repaired) probes may be carried out as follows. Hits are committed when participants correctly press 'yes' when both the shape and the location displayed by the probe were present in the to-be-remembered array (applicable to both intact and re-paired probes). False-alarms (FAs) are committed where participants inappropriately make a 'yes' response when either or both shape and location features displayed by the probe were not present in the to-beremembered array (applicable to both-features- new, new- shape and new- location probes).

To calculate d' for intact probes, hit proportions can be based on this probe type alone, versus total false- alarm proportion committed for all three negative (no) probe types. Similarly, for re-paired probes, d' can be calculated on the basis of hit proportions for repaired probes versus the proportion of false alarms committed for all three negative probe types in total. This procedure yields d' calculations for intact and re-paired probes separately which can be compared with statistical analyses.

Calculating d' For Negative Probes. The aim of this analysis would be to see how well new-shape probes and new location probes were discriminated from both-features-new probes (using false-alarm rates for the three conditions to calculate d')³, and to gauge the magnitude of this difference. As such, two d' scores can be computed, as follows: New-location discrimination from both-features-new (d'), and new-shape discrimination from both-

³ Thanks are due to Michael Verde for advising us on this matter.

features-new (d').

D-Prime where either shapes or locations are attended

The example given relates to when *shapes* are the attended feature. The calculation of d' for positive (intact, re-paired and new-location) probes where shapes only are attended can be carried as follows. Hits (appropriate old responses) are committed when participants correctly pressed 'yes' when the shape displayed by the probe was present in the to-beremembered array (applicable to intact, re-paired and new-location probes). False alarms are committed where participants inappropriately made an 'old' response, by pressing 'yes' when the shape feature displayed by the probe was not present in the to-beremembered array (applicable to both-features-new and new-shape probes). To calculate d' for intact probes, hits proportions are taken for this probe type alone, versus the total false- alarms committed for the two negative probe types (both-features-new, and new-shape probes). Similarly, for re-paired probes, d' can be calculated on the basis of hit proportions for re-paired probes versus false alarm proportions for both negative probe types in total. The same methodology can be applied to calculate d' for new-location probes. This produces d' measures for intact, re-paired and new-location probes separately. Negative probe analysis using d' is carried out as outlined above.

Appendix C

Descriptive statistics for Experiment 1B.

			Quiet Condition (n = 40)					AS Condition (n = 37)				
		А	ccuracy	I	RT	Accuracy		RT				
		(%	Correct)	(Millis	(Milliseconds)		(% Correct)		(Milliseconds)			
Probe	Lag	м	SE	м	SE	М	SE	м	SE			
Intact	250	77.22	2.54	790.81	30.36	83.13	2.54	891.08	40.18			
•	500	77.84	2.22	784.70	32.42	79.92	2.18	893.39	40.87			
	2000	70.66	2.69	810.66	31.52	73.84	2.79	977.85	46.63			
	4000	65.02	3.01	866.63	36.59	66.92	2.98	1005.39	48.56			
Re-paired	250	70.81	3.05	817.64	33.54	76.38	2.23	933.03	34.72			
	500	71.27	2.43	827.14	32.37	78.57	2.08	941.96	40.94			
	2000	58.93	2.67	896.54	39.13	65.90	3.19	1017.87	47.55			
	4000	58.62	2.96	873.08	38.82	60.83	3.21	1060.18	52.17			
Both-Features-New	250	91.90	1.44	660.96	24.57	92.22	1.33	806.95	43.81			
	500	92.53	1.44	643.14	21.42	92.59	1.57	803.73	37.52			
	2000	91.73	1.90	676.64	23.30	93.27	1.22	816.51	39.01			
	4000	93.14	1.53	673.83	26.75	93.94	1.15	825.18	41.63			
New-Location	250	80.5	2.48	726.76	30.32	80.08	2.72	842.39	40.05			
	500	85.81	2.32	665.71	24.07	82.80	2.67	849.55	40.38			
	2000	88.00	1.52	697.89 [′]	25.76	85.50	2.40	864.61	42.20			
	4000	87.99	1.75	700.45	30.67	84.62	2.75	846.01	49.52			
New-Shape	250	67.05	3.00	815.28	33.19	68.44	2.75	938.46	36.85			
•	500	63.93	3.10	837.89	37.31	70.80	2.84	953.34	43.36			
	2000	64.87	2.91	859.95	40.37	69.45	2.88	987.11	50.89			
	4000	63.31	2.88	808.29	29.23	69.62	3.09	982.12	50.06			

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Appendix D

Analysis of all positive probes in Experiment 2A

The following analysis assessed performance for all three positive probe types in Experiment 2A (the shape-relevant task), as only the critical probe conditions (intact and repaired probes) were presented within the text of Series 2.

Reaction Time. Reaction times for intact, re-paired and new-location probes as a function of lag are displayed in Figure D1 (Panel A). A 4 (lag) x 3 (positive probe) ANOVA for repeated measures indicated a significant main effect of lag, F (3, 57) = 9.31, MSE = 25690.31, p < .001; a significant main effect of positive probe, F (2, 38) = 6.01, MSE = 5196.63, p < .01; and finally, no interaction between these factors, F (6, 114) = 1.54, MSE = 4722.17, p = .17.

LSD post-hoc tests on the main effect of positive probe indicated a significant binding effect, p < .01. Reaction times for intact probes were marginally faster than to new-location probes, p = .06. Finally, there was no significant difference in RTs between re-paired probes and new-location probes, p = .10. Trend analysis on the effect of lag indicated a significant linear trend, F(1, 19) = 11.16, MSE = 30133.72, p < .01, and a significant quadratic trend, F(1, 19) = 10.02, MSE = 15525.57, p < .01. While there was an overall tendency for performance to decline over time, inspection of Figure D1 suggests an improvement in RTs between the 250 and 500ms delay intervals which would account for the quadratic component.

In sum, when shapes were task-relevant, there was a significant binding effect for RT measures which was present across all four lag intervals. Further, new-location probe performance did not differ significantly from re-paired probe performance. Finally, analysis of the lag data suggested an improvement in performance between the 250ms and 500ms lag intervals.



Figure D1. The effect of positive probe (and the binding effect) in Experiment 2A. Panel A: significant main effect of positive probe (and binding) ps < .05; significant main effect of lag, p < .05; and no interaction between factors, p > .05 for RT measures. Panel B: a significant main effect of positive probe, p < .05, a marginally significant main effect of binding, p = .06; a significant main effect of lag, p < .05; and no interaction between factors, p > .05 for accuracy measures. Bars represent one standard error of the mean.

Accuracy. Accuracy measures for the three positive probe types as a function of lag are presented in Figure D1 (Panel B). A 4 (lag) x 3 (positive probe) ANOVA for repeated measures indicated a significant main effect of lag, F(3, 57) = 16.51, MSE = 183.80, p < .001; a significant main effect of positive probe, F(2, 38) = 6.36, MSE = 76.21, p < .01, and finally no interaction between factors, F(6, 114) = 2.09, MSE = 125.92, p = .09.

LSD post hoc tests on the main effect of positive probe indicated a borderline significant binding effect, p = .06. Accuracy measures for intact probes were significantly faster than to new-location probes, p < .001, and finally, there was no significant difference in accuracy performance between re-paired and new-location probes, p = .20. Trend analyses on the main effect of lag indicated a significant linear trend in the data, F(1, 19) = 50.85, MSE = 166.40, p < .001, suggesting a linear decline in accuracy as lag increased.

In sum, for accuracy measures the effect of binding was only marginal. Further, newlocation probe performance was equivalent to re-paired probe performance. Finally, trends in the lag data suggested a linear decline in accuracy, as lag increased.

Appendix E

			Shape R	elevant Ta	ask	Location Relevant Task					
		Accu	iracy		RT	Accuracy		RŤ			
		(% Co	orrect)	(Milliseconds)		(% Correct)		(Milliseconds)			
Probe	Lag	M	SE	М	SE	М	SE	M	SE		
Intact	250	90.96	2.66	717.05	30.49	87.21	2.38	661.93	54.74		
	500	87.84	2.05	710.23	26.39	90.97	1.72	602.95	32.77		
	2000	80.34	2.84	756.35	31.27	83.47	1.83	672.60	33.19		
	4000	70.65	3.77	846.55	50.85	84.09	2.59	748.28	54.58		
Re- paired	250	85.03	1.78	773.10	38.22	88.45	3.15	688.08	57.93		
panea	500	85.66	2.45	751.30	30.79	92.21	1.69	597.13	34.50		
	2000	71.90	3.58	773.23	34.36	90.02	2.05	659.00	40.28		
	4000	74.41	3.54	889.73	53.79	84.09	3.31	719.08	56.39		
Both- Features- New	250	84.39	2.43	853.63	32.73	85.02	2.42	687.55	51.40		
	500	81.60	3.06	818.83	29.10	85.65	3.04	647.10	49.03		
	2000	70.95	3.52	847.08	27.23	87.84	3.70	696.13	34.71		
	4000	77.21	3.99	906.65	35.32	82.84	3.79	821.88	75.14		
New- Location	250	84.71	2.15	767.30	34.05	78.15	4.24	705.75	54.66		
	500	80.65	3.45	757.35	31.58	86.58	3.83	667.78	63.11		
	2000	72.84	3.40	769.10	36.20	84.39	4.38	691.80	29.56		
	4000	72.22	3.44	829.40	48.00	78.78	5.08	755.60	57.31		
New- Shape	250	78.15	3.28	832.55	30.45	84.08	4.36	709.50	74.35		
	500	82.22	2.91	818.20	36.34	88.14	2.76	618.10	48.73		
	2000	70.65	3.83	844.75	30.51	85.96	2.02	658.48	29.75		
	4000	71.28	3.55	895.33	41.30	81.59	3.58	756.43	61.46		

Descriptive statistics for Experiment 2 (A & B)

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Appendix F

Analysis of all positive probes in Experiment 2B

The following analysis assessed performance for all three positive probe types in Experiment 2B (the location-relevant task), as only the critical probe conditions (intact and repaired probes) were presented within the text of Series 2.

Reaction Times. Positive probe (intact, re-paired, and new-shape) RT performance as a function of lag is presented in Figure F1 (Panel A). A 4 (lag) x 3 (positive probe) ANOVA for repeated measures indicated a significant main effect of lag, F (3, 57) = 4.47, MSE = 57097.67, p < .05; no significant main effect of positive probe, F (2, 38) < 1; and no interaction between factors, F (6, 114) < 1. Trend analyses on the main effect of lag indicated a significant quadratic trend, F (1, 19) = 7.07, MSE = 53210.82, p < .05, accounted for by a sharp improvement in performance between lags of 250 and 500ms, and a tailing off of performance between the 2000 and 40000ms lags.



Figure F1. The effect of positive probe (and the binding effect) in Experiment 2B. Panel A: a significant main effect of lag, p < .05; no significant main effect of positive probe, p > .05, no binding effect, p > .05; and no interaction between factors for RT measures. Panel B: a marginal effect of lag, p = .06; no significant main effect of positive probe, p = .13, no binding effect, p = .10; and no interaction between factors. Bars represent one standard error of the mean.



probe) ANOVA for repeated measures, which indicated a marginally significant main effect of lag, F(3, 57) = 2.89, MSE = 251.75, p = .06; no significant main effect of probe, F(2, 38) = 2.19, MSE = 130.12, p = .13, and finally no interaction between factors, F(6, 114) < 1. Trend analyses on the main effect of lag suggested a borderline significant cubic trend, F(1, 19) = 4.07, MSE = 53.71, p = .06. Positive probe accuracy measures are presented in Figure F1 (Panel B) as a function of lag. Inspection of Figure F1 (B) indicates a sharp improvement in accuracy measures between the 250- and 500ms lag intervals, followed by a decrease in accuracy between the 500- and 2000ms intervals, and finally, a levelling off of performance (accompanied by a slight increase for intact probes) between the 2000- and 4000 ms intervals, accounting for the cubic trend.

In sum, when spatial location was task-relevant, and shapes task-irrelevant, no evidence of location binding was noted, and performance to all three positive probe conditions was equivalent. Further, positive probe data suggested a period of consolidation between the 250ms and 500ms lag intervals.

Appendix G

The sixty shapes piloted in Experiment 3A (not to scale).

Six point shapes



Appendix H

1. Analysis of all positive probes in Experiment 3B (shape-relevant task)

The following analyses present results for all three positive probe conditions, in Experiment 3B (the shape-relevant task).

Reaction Time: Response times were subjected to a 4 (lag) x 3 (positive probe) x 2 (shape difficulty) ANOVA for repeated measures, with shape difficulty as a between-subjects factor. The analysis indicated a marginal effect of shape difficulty, F(1, 53) = 3.40, MSE = 439117.51, p = .07, whereby RTs were faster in the easy shape condition (M = 729.73, SE = 45.09) relative to the hard shape condition (M = 845.68, SE = 43.89), supporting the distinction between the two sets. Additionally, there was a significant main effect of positive probe, F(2, 70) = 10.29, MSE = 5978.60, p < .001; a significant main effect of lag, F(3, 105) = 2.91, MSE = 31737.19, p < .05, characterised by a significant linear trend, F(1, 35) = 8.24, MSE = 32262.26, p < .01; no interaction between lag and positive probe, F(6, 210) < 1; no interaction between lag and shape difficulty, F(3, 105) < 1; and finally, no three-way interaction between factors, F(6, 210) = 1.35, p = .24.

Post-hoc tests (LSD) on the main effect of positive probe indicated a significant binding effect, p < .001; a significant intact over new-location probe advantage, p < .001; but no difference between re-paired probe RTs and new-location probe performance, p = .85. Finally, there was no interaction between positive probe and shape difficulty, F(2, 70) < 1, indicating that the binding effect was not modified by shape difficulty.

To summarise, the analysis of RT data indicated a significant binding effect, which was not moderated by variations in shape difficulty. In addition, new-location probe performance did not differ to re-paired probe performance. Further, performance was characterised by a linear increase in RTs as lag increased, but this decrement in performance did not modify the binding effect. As in previous experiments, binding emerged within 250ms and could be maintained for at least 4 seconds. Finally, that the easy shape set was in fact easier to remember than the hard shape set was reflected by the RT data. Positive probe RT measures as a function of lag are presented in Panel A of Figure H1 for the easy shape condition, and Panel B of Figure H1 for the hard shape condition.



Figure H1. The binding effect in Experiment 3B (statistics refer to those noted for binding in the main text). Panel A: Significant main effect of binding for RT measures, in the easy shape condition, p < .001. Panel B: Significant main effect of binding for RT measures, in the hard shape condition, p < .05. Panel C: Non-significant main effect of positive probe for accuracy measures in the easy shape condition, p = 15. Panel C: Significant main effect of binding in the hard shape condition, p < .01. Bars represent one standard error of the mean.

Accuracy. Accuracy measures were subjected to a 4 (lag) x 3 (positive probe) x 2 (shape difficultly) ANOVA for repeated measures, with shape difficulty as a between-subjects factor. Data are presented in Figure H1 (Panel C & D, for the easy and hard shape sets, respectively). The analysis indicated no significant main effect of shape difficulty, F(1, 35) < 1 (easy shapes: M = 82.89, SE = 1.98; hard shapes: M = 80.62, SE = 1.93). Further, there was

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a significant main effect of positive probe, F(2, 70) = 6.37, MSE = 83.10, p < .01; a significant main effect of lag, F(3, 105) = 9.31, MSE = 142.48, p < .001, characterised by a significant linear trend, F(1, 35) = 21.73, MSE = 167.86, p < .001; and no interaction between these factors, F(6, 210) < 1. Finally, there was no significant interaction between lag and shape difficulty, F(3, 105) < 1; and no three-way interaction between factors, F(6, 210) < 1. Critically, the probe factor and the shape difficulty factor did not interact, suggesting that (as in the RT analysis) the binding effect was not modified by shape difficulty, F(2, 70) < 1.

LSD post-hoc tests on the main effect of positive probe indicated a significant binding effect, p < .001; significantly better accuracy performance for intact probes relative to new-location probes, p < .05; and no performance difference between re-paired and new-location probes, p = .19.

In sum, for accuracy measures there was a significant binding effect which remained across manipulations of shape difficulty. There was no interaction between positive probe and shape difficulty, yet planned comparisons presented on accuracy data in the main text suggested that the binding effect was only significant for the hard shape condition.

Appendix I

Descriptive statistics for Experiment 3B (the shape-relevant task).

				Hard Shape Condition					
		Accu	Accuracy (% Correct)		RT (Milliseconds)		су	RT (Milliseconds)	
		(% Co					rrect)		
Probe	Lag	<u>M</u>	<u>SE</u>	<u>M</u>	SE	M	SE	_M	SE
Intact	250	87.87	2.45	663.22	31.43	87.86	2.00	774.08	62.89
	500	88.89	3.30	671.67	25.91	83.25	2.95	850.63	62.71
	2000	79.54	3.91	731.61	35.83	82.26	2.76	839.71	56.56
	4000	80.92	3.25	751.53	42.15	79.31	3.28	830.92	65.47
Re-paired	250	85.44	2.90	701.11	32.25	79.63	2.61	845.05	57.01
	500	82.32	2.82	722.11	31.62	82.92	3.34	860.82	61.16
	2000	79.53	3.88	751.17	40.71	75.35	3.26	851.39	52.81
	4000	79.53	3.91	801.08	42.63	75.02	3.35	870.63	63.85
New-Location	250	88.92	2.05	707.22	37.09	84.23	1.99	805.92	54.64
	500	83.36	3.19	737.08	31.15	81.28	2.95	862.34	62.12
	2000	79.89	2.65	746.86	40.27	77.66	3.15	880.63	59.47
	4000	78.50	3.36	772.03	39.21	78.65	3.39	876.00	69.9
Both-Features-New	250	77.11	3.57	788.17	34.84	76.02	3.29	938.42	66.0
	500	77.80	2.78	768. 9 4	23.17	73.38	3.94	1001.32	68.4
	2000	77.45	3.51	807.81	30.08	72.39	3.95	967.34	54.6
	4000	77.12	3.16	836.36	27.35	68.45	3.81	960.89	72.2
New-Shape	250	71.89	3.40	760.00	25.97	67.13	5.45	898.37	60.1
	500	76.06	2.69	781.06	26.07	66.81	4.25	968.13	66.0
	2000	76.41	3.41	818.83	28.34	65.16	3.86	956.61	55.5
	4000	73.63	4.39	843.42	32.94	<u>61.5</u> 4	5.48	936.16	75.6

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Appendix J

1. Analysis of all positive probes in Experiment 3C (location-relevant task)

Reaction Time. RT data were subjected to a 4 (lag) x 3 (positive probe) x 2 (shape difficulty) ANOVA for repeated measures, with shape difficulty as a between-subjects factor. The analysis indicated no significant main effect of shape difficulty, F(1, 34) = .002, MSE = 375290.77, p = .97 (easy shapes: M = 633.07, SE = 41.68; hard shapes: M = 635.67, SE = 41.68); no significant main effect of positive probe, F(2, 68) = 1.56, MSE = 2570.64, p = .22; and a significant main effect of lag, F(3, 102) = 9.16, MSE = 16316.49, p = .01, characterised by a significant linear trend, F(1, 34) = 24.67, MSE = .54, p < .001, and a significant cubic trend, F(1, 34) = 6.47, MSE = 13825.67, p = .02. Post-hoc planned comparisons (LSD) confirmed that there was no significant binding effect, p = .58. Finally, there was no interaction between positive probe and shape difficulty, F(2, 68) = 1.05, p = .36.

The data further indicated no significant interaction between lag and positive probe, F (6, 204) = 1.52, MSE = 4163.22, p = .20; no interaction between lag and shape difficulty, F (3, 102) < 1; and finally no three-way interaction between factors, F (6, 204) = 1.42, p = .21. Positive probe RT measures as a function of lag for the easy and hard shape conditions are presented in Panel A and B of Figure J1, respectively.

In sum, for RT measures there were no performance differences between positive probe types, indicating that all three were treated similarly. This finding suggests that the shape information related to the spatial location could be disregarded when the task required focus on only spatial location. Additionally, trends in the lag data indicated significant linear and cubic trends. As in previous experiments the results are suggestive of an improvement in performance between the 250ms and 500ms lag intervals.



Figure J1. Positive probe performance in Experiment 3C (statistics refer to those noted in the main text for binding). Panel A: RT measures indicating no significant binding effect for the easy shape condition, p > .05. Panel B: RT measures denoting no significant binding effect for the hard shape condition, p > .05. Panel C Accuracy measures indicating no significant binding effect for the easy shape condition (P > .05). Panel D: Accuracy measures indicating no significant binding effect in the hard shape condition (P < .05). Bars represent one standard error of the mean.

Accuracy. Accuracy data were subjected to a 4 (lag) x 3 (positive probe) x 2 (shape difficulty) ANOVA for repeated measures, with shape difficulty as a between-subjects factor. The analysis indicated a significant main effect of shape difficulty, F (1, 34) =11.44, MSE = 164.35, p < .01, whereby accuracy performance was superior in the hard shape condition (M

= 90.62, SE = .87) relative to the easy shape condition (M = 86.45, SE = .87). There was no significant main effect of positive probe, F(2, 68) = 2.07, MSE = 51.20, p = .13; a significant main effect of lag, F(3, 102) = 7.31, MSE = 99.22, p < .001, characterised by a significant linear trend, F(1, 34) = 17.27, MSE = 164.35, p < .01; and no interaction between these factors, F(6, 204) = 1.60, MSE = 79.94, p = .17. Shape difficulty and positive probe did not interact, F(2, 68) < 1. Finally, there was a marginal interaction between lag and shape difficulty, F(3, 102) = 2.52, p = .06, but no three-way interaction between factors, F(6, 204) = 1.62, p = .14.

LSD post-hoc tests on the main effect of positive probe indicated no binding effect, p = .99, no difference in performance between intact and new-shape probes, p = .12, and finally no difference between re-paired and new-shape probes, p = .11. As in the RT analysis, for accuracy measures there were no performance differences between the three positive probe types, further suggesting that shape information could be disregarded, or adequately ignored, when focussing on the spatial locations. Furthermore, accuracy in the hard shape condition was significantly better than in the easy shape condition.

Appendix K

Descriptive statistics for Experiment 3C (the location-relevant task).

		Easy Shape Condition			Hard Shape Condition				
		Accuracy		RT		Accuracy		RT	
		(% Correct)		(Milliseconds)		(% Correct)		(Milliseconds)	
Probe	Lag	м	SE	М	SE	М	SE	M	SE
Intact	250	89.86	2.10	613.44	51.36	95.16	1.48	597.86	26.28
	500	86.83	1.95	592.14	53.01	91.69	1.52	577.25	22.99
	2000	88.22	2.36	625.28	50.96	84.75	1.69	689.50	20.75
	4000	84.05	2.99	685.89	63.41	91.69	1.51	684.39	38.54
Re-paired	250	89.96	2.09	620.25	62.06	90.99	2.03	607.67	25.60
	500	92.39	1.86	620.97	56.85	94.30	1.08	581.22	27.24
	2000	84.41	1.70	641.28	59.63	89.26	1.59	650.14	25. 78
	4000	82.32	2.59	651.25	57.42	88.57	1.97	665.28	37.24
New-Shape	250	87.18	1.71	625.56	58.93	92.72	2.04	631.22	35.26
	500	84.74	2.87	588.64	55.44	93.24	1.72	592.86	23.86
	2000	87.18	1.7 9	642.50	57.96	86.30	2.33	679.17	16.63
	4000	80.23	3.12	689.64	61.05	88.73	2.04	671.50	35.96
Both- Features New	250	78.50	2.78	703.75	52.70	82.13	3.05	666.53	29.02
	500	86.83	2.13	643.67	56.02	89.78	1.67	637.11	29.98
	2000	86.48	2.16	665.86	54.86	88.21	1.81	708.94	23.57
	4000	81.97	2.72	716.53	50.77	86.82	2.08	714.44	41.55
New-Location	250	72.24	4.29	688.69	64.87	82.49	2.87	687.25	35.67
	500	86.13	2.84	647.36	57.91	88.06	2.58	626.89	19.99
	2000	83.02	2.41	670.58	52.09	80.93	2.45	703.86	19.51
	4000	80.23	2.68	715.06	49.76	88.04	2.55	722.97	39.90

Appendix L

Experiment 4: Accuracy on the Digit Task

The present analysis assessed the level of accuracy achieved on the digit load task as a function of probe type, over the four lag intervals in Experiment 4. Load task accuracy data were subjected to a 4 (lag) x 5 (probe type) ANOVA for repeated measures. The analysis indicated no significant main effect of lag, F(3, 117) < 1; no significant main effect of probe type, F(4, 156) < 1; and finally, no interaction between factors, F(12, 468) < 1. The data are presented in Figure L1A for positive probe trials, and L1B for negative probe trials (separated for ease of viewing).



Figure L1. Performance on the load task. Panel A: Accuracy on the load task during positive probe trials. Panel B: Accuracy on the load task for negative probe trials. Bars represent one standard error of the mean.

Appendix M

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Descriptive statistics for Experiment 4.

		No Load Condition			Load Condition				
		Accu	racy	RT		Accuracy		RT	
		(% Co	rrect)	(Milliseconds)		(% Correct)		(Milliseconds)	
Probe	Lag	M	SE	м	SE	М	SE	M	SE
Intact	250	78.44	2.91	737.15	31.11	77.19	2.83	804.68	35.23
	500	79.69	2.48	750.45	26.93	81.11	2.70	768.12	28.32
	2000	72.34	2.68	813.29	42.49	74.25	2.66	798.74	31.35
	4000	62.34	3.81	879.16	45.37	69.62	2.84	826.74	39.91
Re-	250	72.03	2.15	786.79	30.89	74.05	2.69	801.29	31.97
paired	500	72.19	2.85	836.68	36.65	75.99	2.40	807.17	26.76
	2000	65.00	3.39	848.10	39.79	68.93	2.89	818.32	31.74
	4000	58.44	3.01	926.99	45.35	62.68	2.94	853.69	37.97
Both- Features- New	250	90.47	1.90	683.23	20.40	90.32	1.99	702.10	31.83
	500	93.13	1.0 9	681.70	24.16	94.04	1.95	670.21	27.46
	2000	92.50	1.29	704.19	32.69	93.49	1.51	673.10	31.49
	4000	92.50	1.29	749.10	42.35	93.49	1.51	726.82	30.37
New- Location	250	79.69	2.54	729.23	29.60	82.91	2.60	729.01	34.52
	500	87.50	2.00	713.13	31.09	86.58	2.30	669.73	30.86
	2000	88.59	2.18	730.69	40.86	87.62	1.85	708.33	30.11
	4000	87.03	1.89	748.65	37.85	82.64	2.54	752.99	35.76
New- Shape	250	69.06	3.30	797.65	29.81	59.24	3.03	802.53	38.51
•	500	66.41	2.51	821.28	24.40	61.36	3.21	807.54	24.47
	2000	68.13	3.59	832.75	32.01	59.41	3.15	836.19	34.42
	4000	66.72	3.50	871.81	32.84	58.90	3.38	908.46	49.42

SUBSCALE	FORM(s)	POSSIBLE RANGE	ITEMS	
Internal	A, B, C	6 - 36	1, 6, 8, 12, 13, 17	
Chance	A, B, C	6 - 36	2, 4, 9, 11, 15, 16	
Powerful Others	A, B	6 - 36	3, 5, 7, 10, 14, 18	
Doctors	С	3 - 18	3, 5, 14	
Other People	С	3 - 18	7, 10, 18	

SCORING INSTRUCTIONS FOR THE MHLC SCALES

The score on each subscale is the sum of the values circled for each item on the subscale (i.e., where 1 = "strongly disagree" and 6 = "strongly agree"). No items need to be reversed before summing. All of the subscales are independent of one another. There is no such thing as a "total" MHLC score.

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