How Does Our Ability to Integrate Information Across Space and Time Change As We Age?

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Abstract

This thesis investigated the nature of changes in feature binding ability that occur as a function of healthy ageing. Under the premise that these changes may occur due to reduced attentional resources (Sylvain-Roy et al., 2005), or changes in the ability to use contextual information as cue for recall (Meulenbroek et al., 2010), two hypotheses were tested; the *ageing-attention hypothesis*, and the *ageing-context hypothesis*. These hypotheses were tested under intentional binding instructions (e.g. Allen et al., 2006), and incidental binding instructions (e.g. Campo et al., 2010) which also included tests of whether nearby contextual information or absolute location are used in location binding (e.g. Olson & Marshuetz, 2005). The thesis found no support for either the ageing-attention hypothesis or the ageing-context hypothesis. The most valuable findings were the effortful nature of younger adult incidental location binding, and perhaps more crucially, the demonstration that older adult binding deficits may be best explained in terms of inhibitory deficit and differences in processing style between older and younger adults.

Thesis Outline

Binding is an important determinant of visual short-term memory (VSTM) performance, yet the effects of normal cognitive ageing on binding in VSTM are not yet well understood. Though we experience the world in terms of intact objects within coherent scenes, the features from which this experience is comprised (e.g. colours, shapes, & locations) are initially processed in separate cortical regions (Tootell et al., 1996). This leaves the cognitive system with two challenges: (1) to correctly construct objects from the constituent features, and (2) in relation to working memory (WM), to make these bound representations available once the objects are no longer in view. This thesis investigates the effects of healthy cognitive ageing on feature binding ability through two hypotheses: the ageing-attention hypothesis, that the reduced attentional capacity that occurs as a function of healthy ageing (Sylvain-Roy et al., 2005) drives differences in feature binding ability; and the ageing-context hypothesis, that changes in feature binding ability as a function of healthy ageing occur due to older adults' inability to use contextual information as a cue for recall (Meulenbroek et al., 2010).

Existing studies suggest that surface-feature binding (e.g. between colour & shape) seems to be relatively unaffected by age (e.g. Allen et al., 2006; Parra et al., 2009); while there is some limited evidence that location-binding deficits manifest in older adults (e.g. Cowan et al, 2006). These two classes of bindings have previously been distinguished on both developmental (e.g., Oakes et al., 2006) and neurological grounds (Piekema et al., 2006). Very few studies have assessed the two classes of feature binding in a single paradigm; as such Chapter 2 in this thesis adapts the paradigm of Allen et al. (2006) and Brown & Brockmole (2008) to allow the assessment of both surface-feature binding, and location binding. In each experiment participants completed a change detection paradigm, where they were instructed to remember either single features (colour, shape, location) or binary combinations of those features (colour & shape, colour & location, shape & location), with binding ability assessed through comparisons between performance in each binary combination condition and its constituent features. Assessing the ageing-context hypothesis (Experiments 1 & 5), and the ageing-attention hypothesis (Experiments 2-4), Chapter 2 demonstrated no differences in surface-feature binding ability or location binding ability either as a function of healthy ageing, or attentional capacity.

Under the premise that the intentional feature binding assessed in the previous chapter may differ from incidental feature binding (binding features when it is not explicitly instructed prior to encoding), Chapter 3 moved to the assessment of incidental feature binding. Directly replicating the method of Campo et al. (2010), Experiment 6 tested the ageing-context hypothesis by testing younger and older adults on incidental binding between letters and locations. The established findings in this paradigm are that of a 'binding asymmetry' whereby letters are bound to locations when letters are task relevant (and locations are to be ignored), but not when locations are task relevant. Performance approached ceiling in all conditions, but was suggestive of binding between letters and locations, irrespective of which feature was task relevant, and irrespective of age group. Adjustments needed to be made to both draw performance away from ceiling, and additionally, to make the experiments more directly comparable to those in Chapter 2. Following this, Experiment 7 repeated the design of the prior experiment but utilised difficult to name shape stimuli to both draw performance away from ceiling and make the experiment more directly comparable to Chapter 2. Although younger adults again failed to show the binding asymmetry expected, older adult performance showed an unanticipated asymmetry but one opposite to that typically shown by younger adults. Results are discussed in terms of feature binding, and feature inhibition theory casting doubt on the ageing-context hypothesis. The final study in Chapter 3 explored the ageing-attention hypothesis by replicating the method of Experiment 8, but testing younger adults under low and high cognitive load. Cognitive load was induced by varying the difficulty of concurrent articulation, such that under low cognitive load, participants repeated a randomly displayed number out loud for the duration of the trial, while in the high cognitive load condition, participants counted backwards in threes from that number. This time, the expected asymmetry was shown in the low load condition, but in the high load condition there was no evidence of binding with either feature task relevant. The difference in the pattern of results between the older adults in Experiment 7, and the younger adults in the high load condition of Experiment 8, again refutes the ageing-attention hypothesis.

Chapters 2 and 3 showed mixed findings in respect of an older adult location binding deficit shown. As such, Chapter 4 investigated first the extent to which objects are (incidentally) bound to either relative or absolute spatial location in a task when object identity only is task relevant (Olson & Marshuetz, 2005), and second whether older adults differ to younger adults in the way in which they incidentally bind objects to locations. Experiment 8 used an adapted form of the paradigm of Olson & Marshuetz (2005) that separated the testing of relative and absolute location binding in a way not previously possible. The experiment showed no differences in the performance of younger and older adults standing in direct contrast to previous incidental binding experiments in this thesis.

The final chapter summarises the key findings from the thesis and is discussed by contrasting the findings across chapters. In summary this thesis ultimately rejects both hypothesises (Ageing-Attention Hypothesis, that performances differences that occur as a function of ageing are best explained in terms of declines in attentional resources; Ageing-Context Hypothesis, that these age related performance changes are best explained in terms of changes in one's ability to use context as a cue for recall). Ultimately suggesting instead that older adult changes in feature binding may be better explained in terms of changes in cognitive approach to the task, with results perhaps indicating that older adult performance is better explained in terms of inhibitory deficits, than in terms of working memory deficits, with these differences leading to the tasks being completed in a different cognitive manner.

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And finally, hello to Jason Isaacs.

Author Declaration

I hereby declare that the work presented in this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

Peer-Reviewed Abstracts

Conferences:

Chapter 2: **Ferneyhough, S.M.**, Elsley, J.V. & Johnson, A. (2013). The effects of normal cognitive ageing on surface-feature and location binding in visual short term memory. NQA Oral Presentation at Joint Annual Conference of the BPS Developmental and Cognitive Sections. Sept. 6th.

Chapter 2: **Ferneyhough, S.M.**, Elsley, J.V. & Johnson, A. (2014). The effects of ageing on the incidental binding of objects and locations. Poster Presentation at BPS Cognitive Section Conference, Nottingham Trent: Sept

Chapter 3: **Ferneyhough, S.M.**, Elsley, J.V. & Parmentier, F.B.R. (2014). Contrasting the role of attentional resources in surface-feature binding and location binding in visual short term memory. Poster Presentation at the International Conference on Working Memory, Cambridge: July 11th.

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Chapter One: Literature Review

1. Introduction

1.1 The binding problem in visual short-term memory

Visual short-term memory (VSTM) is the cognitive system responsible for the temporary storage of visual information. Phillips' (1974) conducted a seminal study into the separation between VSTM and sensory storage showing that complexity affected memory performance when the retention interval exceeded 100ms, when the matrix was moved during the retention interval, or when some form of masking was present. This was taken to indicate that there exists two forms of memory in respect of visual information; (1) a sensory store highly sensitive to visual interference such as masking or stimulus movement and severely time limited, and (2) a separate visual short-term memory store argued to not be related to spatial location. A central thread of research into VSTM has sought to establish the manner in which objects are represented and how the mode of object representation relates to VSTM capacity (currently considered to be four to five items depending on the stimuli to-be-remembered; Pashler, 1988; Luck & Vogel, 1997; Simons, 1996). Indeed, while the limited nature of VSTM capacity is not disputed, the nature of capacity limitations is less well understood. Specifically, there is some disagreement in the literature as to how to quantify capacity limitations. Some argue that capacity is best expressed in terms of the number and/or nature of visual features present in a display (e.g., colours, shapes, locations; Matthey, Bays & Dayan, 2015; Oberauer & Eichenberger, 2013). Others suggest the number of objects present in the display is the limiting factor (e.g., Alvarez and Cavanagh, 2004; Luck & Vogel, 1997). While a final proposal is that of combination of these two factors (e.g. Wheeler & Treisman, 2002).

Supporting the idea that VSTM capacity is defined by the number of multi-feature 'objects' present in a display, many studies have demonstrated that VSTM capacity may be increased through a process of *feature binding*. Feature binding allows VSTM to combine the visual (e.g., colour, shape) and spatial (e.g., location, trajectory of motion) aspects of a stimulus or event so that they may be maintained as coherent "wholes" over short periods of time. In a seminal study, Luck and Vogel (1997) demonstrated that while participants could only retain around four colour features or four orientation features, they could equally remember four objects defined by both colour and orientation. Furthermore, when objects were each composed of four features, memory span remained at around four objects suggesting that VSTM capacity should be considered as defined by the number of objects rather than the number of features present in a to-be-remembered array. Other authors, however, have instead argued that feature memory should be considered separately to object memory meaning that both may influence capacity limitations (Matthey, Bays & Dayan, 2015; Oberauer & Eichenberger, 2013). For instance, Oberauer and Eichenberger (2013) found evidence to suggest that the capacity of VSTM is limited both by the number of bound objects, but also the fidelity of memory representations for features (e.g., colour, orientation, shape, size). Nevertheless, memory capacity can clearly be extended through the process of feature binding.

Beyond extending memory capacity, the process of feature binding also underpins memory for coherent object and scene representations, a process that creates a challenge for the cognitive system, with each visual feature dimension (e.g., colour , size, shape, & location) processed separately by feature-specific modules in the visual cortex (Livingstone & Hubel, 1988; Tootell et al., 1996). Thus, the cognitive system needs to correctly combine features into unified wholes - referred to as the *binding problem* (Herzog, 2009; Howe, & Ferguson, 2015; Treisman, 1996; Wolfe, 2012). This seemingly effortless process represents a particular challenge for some subsets of the population. For instance, binding ability has been shown to be deficient in those with dyslexia (Jones, Branigan, Parra & Logie, 2013) who appear deficient in their use of location information to assist in recall of visual-phonological pairings. This is thought to partly explain the reading difficulties of those with dyslexia in comparison to those without. Such deficits are also present in those with Alzheimer's disease (AD). Comparing memory performance in healthy older adults and those with AD often shows memory for bound combinations of features to be deficient while memory for individual features remains relatively intact (Parra et al., 2009, 2010). Similar is shown in respect of those with Balint's syndrome, a triad of neurological impairments rendering those with the condition unable to perceive the visual field as a whole (simultanagnosia), experiencing difficulty in fixating on specific points (oculomotor apraxia) and unable to move their hand to a specific object using vision (optic ataxia; Perez, Tunkel, Lachmann, & Nagler, 1996). Balint's syndrome leaves those with the condition unable to demonstrate memory for bound combinations of features above chance level, thought to represent inability to attentively consolidate perceived associative relationships (Cinel & Humphreys, 2006). More pressing for this thesis are suggestions that older adults exhibit issues in binding objects to locations (e.g. Cowan, Naveh-Benjamin, Kilb & Saults, 2006; Kessels, Hobbel & Postma, 2007; Mitchell, Johnson, Raye, Mather & D'Esposito, 2000) discussed in depth in Chapter 1.6.

While feature binding is widely considered an important influence on VSTM performance, there are currently several areas of disagreement in the literature. The first pertains to the degree to which memory capacity should be defined by the number of features present in a display, the number of objects, or both (Alvarez and Cavanagh, 2004; Luck & Vogel, 1997; Matthey, Bays & Dayan, 2015; Oberauer & Eichenberger, 2013; Wheeler & Treisman, 2002). Indeed, it may be the case that there are different types of binding, each with their own cognitive characteristics. The second pertains to the degree to which feature binding in VSTM is an effortless process (i.e., one that does not draw upon attentional resources any more than memory for individual features – e.g. Allen et al., 2006; Elsley & Parmentier, 2009), indeed, this factor may depend on the type of binding under assessment; and relatedly, the third relates to the trajectory of decline in feature binding performance as a function of normal cognitive ageing (e.g. Brown & Brockmole, 2010; Cowan et al., 2006). This thesis investigates these inconsistencies. It starts below with discussion of feature binding as it is understood in the context of visual perception –a body of research closely related to feature binding in VSTM that suggests different classes of binding may exist (Chapter 1.2). This thesis will then explore the extent to which the binding process in VSTM draws upon cognitive effort relative to the maintenance of individual features, and whether the cognitive demand varies as a function of the type of binding in question (Chapter 1.3). Finally, this thesis assesses the extent to which binding performance declines as a consequence of normal cognitive ageing and again, whether this decline is sensitive to the type of binding under investigation (Chapter 1.4).

1.2 Perceptual Feature Integration, Types of Binding and VSTM

The cognitive processes of perception and VSTM are closely related, with some theorists considering the latter the sustained maintenance of the former once percepts are no longer in view (Hollingworth & Rasmussen, 2010; Treisman & Zhang, 2006, Treisman, 2006). Perhaps unsurprisingly then, recent VSTM investigations have suggested that similar principles may apply to binding in VSTM as have been long established in the perceptual binding literature. In particular, these investigations suggest it may be useful to consider the binding of surface features (the visual properties of an object that combine to provide its visual identity) separately to the representation of objects in their locations (discussed in detail in Chapter 2). For this reason, it is useful to begin this subsection with discussion of the perceptual feature integration literature and, in particular, Feature Integration Theory (Treisman & Gelade, 1980).

1.2.1 Surface Feature Binding, Location Binding & Feature Integration Theory

Theoretical accounts of visual processing in perception and memory often suppose independence in the representation of features comprising 'what' objects are and the representation of the locations of those features ('where' they are e.g., Feature Integration Theory; FIT, Treisman & Gelade, 1980; The Working Memory Model: Baddeley & Hitch, 1974; Baddeley, 2000; Baddeley, Allen & Hitch, 2011). For instance, FIT prescribes that features are detected early in the visual process with each type of surface feature (e.g. colour or shape) held separately alongside a 'master map' of locations, which marks the positions in space where objects are located. Feature binding is achieved by virtue of visual features' shared spatial location - attention is guided to a specific area of the 'master map of locations' and the surface features in that location increase in activation, combining to create a distinct object. Thus, according to FIT, surface features are stored separately to locations, with the features being bound together by virtue of attention falling upon their shared position in space (Figure 1.1) which, in turn, is represented independently from surface-features on the master map of locations.

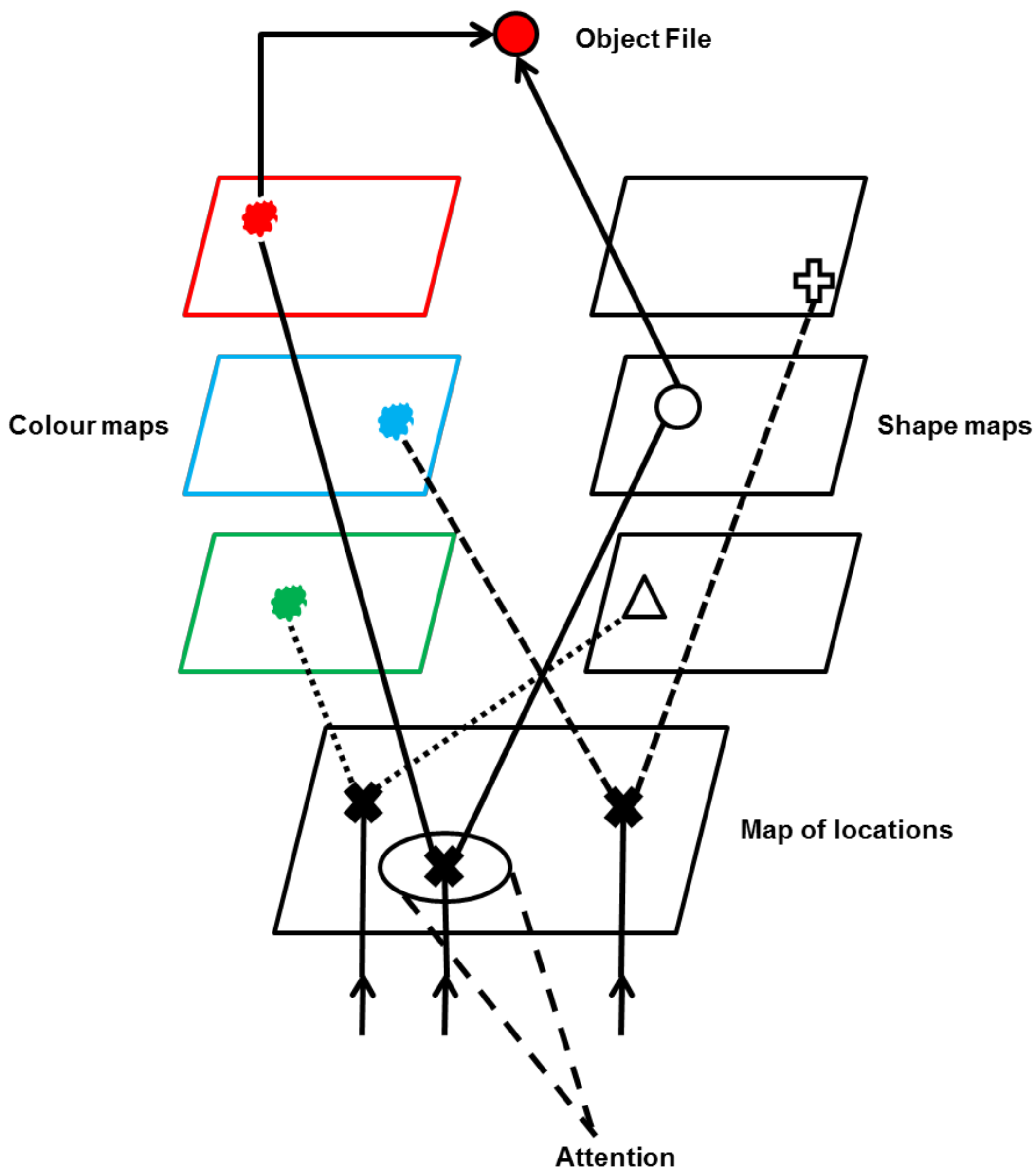


Figure 1.1. The creation of an object-file in accordance with Feature Integration Theory (FIT; adapted from Triesman & Gelade, 1980).

A similar distinction between the representation of surface features and spatial locations has recently been drawn in the VSTM literature, through the proposal of two potentially functionally distinct classes of feature bindings. *Surface feature binding* refers to the combining of visual features such as colour and shape to create a single discriminable object identity (for example, a green square; Allen, Baddeley & Hitch, 2006). In contrast, *location binding* refers to the binding of an object to a specific location in space (Cowan et al., 2006). Anecdotally, each type of binding would appear to serve a different function: surface-feature binding provides object identity and consists of associations between features that are likely to remain consistent over time. In contrast, location binding is likely to be changeable as objects are moveable (likewise, an objects position in space may change, while its identity typically remains stable). This distinction (which echoes that extant in the perceptual feature integration literature) is supported by several lines of evidence. For example, Piekema et al. (2006) showed hippocampal activity specific to location binding that was not present during surface-feature binding. The two types of binding even seem to diverge in their developmental trajectories in infancy. For example, Slater, Mattock, Brown, Burnham, and Young (1991) suggest that visual features of objects (in this case colour and orientation) are processed separately until the age of approximately 3 months at which point the combinations of features can be remembered. Connections between surface features and locations, however, are not possible until later in development (approximately 6.5-7.5 months of age: Oakes, Ross-Sheehy & Luck, 2006). Finally, and critically for the current review, based on existing evidence, the two classes of binding appear to diverge in their recruitment of attentional resources. This latter point is discussed further below (Chapter 1.3) in the context of the Working Memory Model (Baddeley & Hitch, 1974; Baddeley, 2000; Baddeley, Allen & Hitch, 2011) and later on with reference to cognitive ageing (Chapter 1.4). In sum, investigating potential mechanistic differences between surface-feature bindings and location bindings in terms of their attentional requirement and trajectory of decline in ageing are the two primary goals of this thesis.

1.3 Binding, Attention and the Working Memory Model

An influential model of short-term memory function is the working memory model (Figure 1.2; Baddeley & Hitch, 1974; Baddeley, 2000). The original tripartite model proposed a central executive controlling two slave systems acting as stores for visuo-spatial information and verbal information: the visuospatial sketchpad and phonological loop, respectively (Baddeley & Hitch, 1974; Baddeley, 2000; Baddeley, Allen & Hitch, 2011). Of note, this model presupposes the separate storage of different feature types (e.g. verbal information in the phonological loop and visuo-spatial location information in the visuo-spatial sketchpad). Building on this, Logie (1995) suggests that the visuo-spatial sketchpad should itself be subdivided into the visual cache, which stores form and colour information, and the inner scribe, which processes spatial information and movement. As the central executive had no storage of its own, and each store could only process a specific type of information, the model was not initially able to account for the ability to combine features from disparate stores, for example remembering the spatial location of verbal information or the colour of the text in which a word is presented. Thus, Baddeley (2000) added a new component that accounted for this shortfall; the episodic buffer (Figure 1.2). The episodic buffer component has the ability to combine information from the separate stores within working memory, perceptual input and long-term memory, which it converts into, then stores in multidimensional code. Critically, and as previously mentioned, a common question in feature binding research is whether the process of binding features together occurs automatically (requiring little to no cognitive effort beyond that required in maintaining memory for individual features), or whether binding is an active, cognitively demanding process (Allen et al., 2006; Elsley & Parmentier, 2009). Indeed, that feature binding should be an effortful process was a key prediction of the episodic buffer as initially proposed, because access to the buffer from the slave systems was assumed to occur via the central executive (and conscious awareness). Hence the episodic buffer was not assumed to be an implicit (automatic) system (Baddeley, Allen & Hitch, 2011) as any binding process occurring within the buffer was subject to the attentional gatekeeping of the central executive.

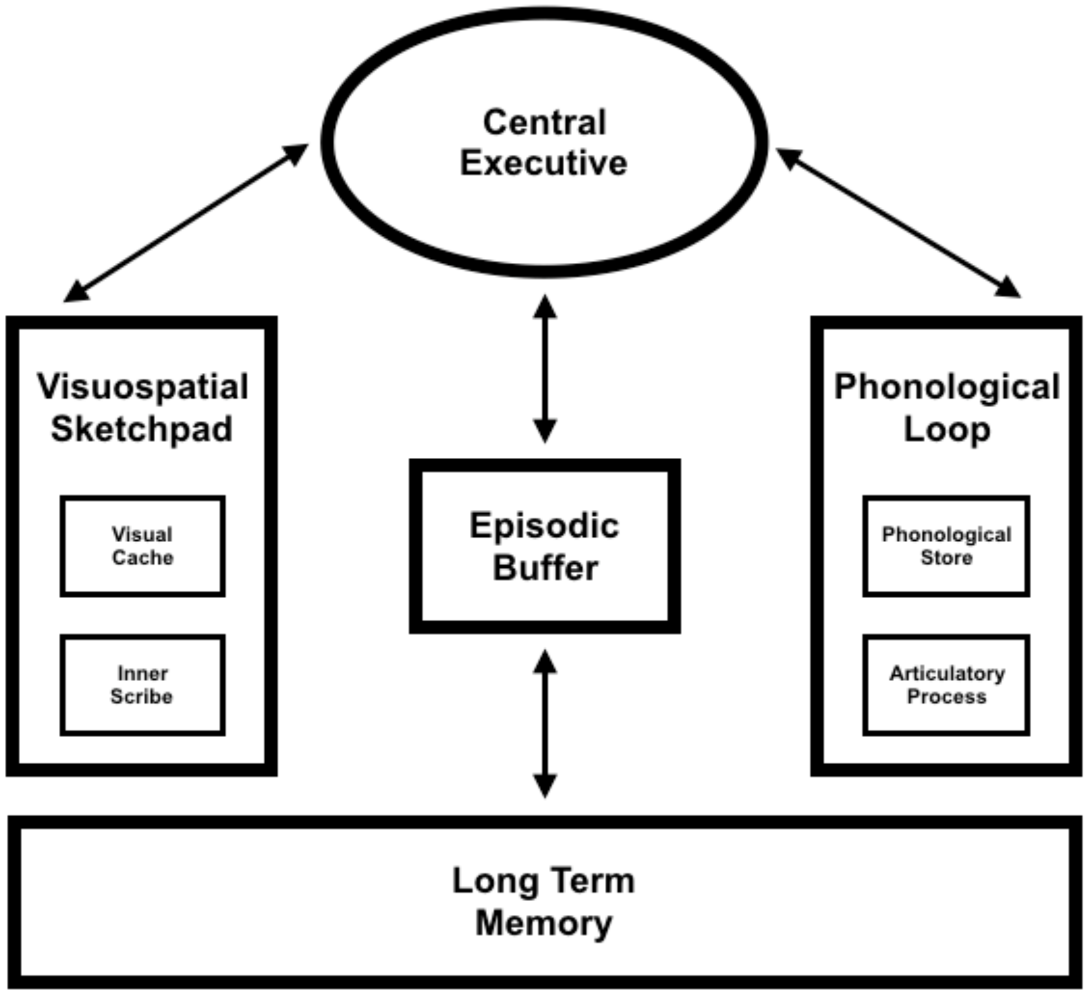


Figure 1.2. Working Memory Model (adapted from Baddeley, 2000) with the addition of the visual cache and inner scribe (Logie, 1995).

Whether or not feature binding is an effortful process has been assessed using a variety of task variations including manipulations of set-size and the number of features comprising each object (e.g., Luck & Vogel, 1997); the implementation of a cognitive load (e.g., Allen et al., 2006; Allen et al., 2012; Brown & Brockmole, 2010) and the implementation of a suffix (e.g., Ueno et al., 2011a, b). Each of these lines of evidence is discussed in turn below in the context of surface-feature binding. A discussion of evidence relating to location binding will follow thereafter (Section 1.4 below).

1.3.1 The role of cognitive effort in surface-feature binding in VSTM: Set size

One way to assess whether bound objects (rather than individual features) are the units of VSTM capacity is to systematically vary set size (the number of objects present in an array) and the number of features comprising each of those objects. The rationale is simple: if memory capacity is defined at the level of bound objects, adding further features to each of those objects should do little to compromise performance as long as the number of objects does not exceed the capacity of VSTM. Studies using this method have also been used to inform on, albeit indirectly, whether or not the binding process occurs automatically. Using this logic, Luck and Vogel (1997) suggest that surface feature binding is indeed an automatic process, with memory for four visual stimuli, each with two features (e.g. bi-coloured squares), comparable to memory for four visual stimuli each consisting of eight individual features. Their finding therefore provides indirect evidence that surface-features are bound drawing on little to no cognitive effort. While often cited as the seminal demonstration of feature binding in VSTM, the finding is not without some controversy. For instance, Wheeler and Treisman (Experiment 1; 2002) failed to reproduce Luck and Vogel's (1997) bi-coloured square findings, instead showing that memory capacity was limited by the number of individual features rather than the number of bi-coloured objects (squares containing two colours). In particular, participants showed difficulty in combining features from the same dimension (e.g., two colour features, as was the case with bi-coloured squares). They fared better at binding across features dimensions (e.g., colour-shape objects), but memory capacity was limited at larger set sizes with set sizes of six consistently eliciting poorer performance than smaller set sizes, irrespective of whether capacity is calculated in terms of the number of features, or the number of objects. This brings with it the suggestion that the capacity of VSTM may in fact be considered at two levels; a limit on the capacity of memory for a single features (constrained by nature and type), and a secondary limit on the number of objects (bound combinations of features). This is the explanation of VSTM capacity proposed by Oberauer and Eichenberger (2013) who demonstrated that change detection performance declines as the number of features to be remembered for each object increases; but particularly when the features come from the same dimension e.g. multiple colours in a single object and when those features were high in complexity. As such, it appears that binding can indeed improve VSTM capacity, subject to certain limitations. Other studies have investigated the role of cognitive effort more directly by assessing binding performance when attentional resources are unavailable to direct towards the binding together of features, this is discussed below.

1.3.2 The role of cognitive effort in surface-feature binding in VSTM: Cognitive Load

Taking a different but more direct tack, some research has employed the addition of a cognitively demanding concurrent cognitive load during tasks assessing memory for individual features and binding between those features. The rationale of these studies is that if a process draws more heavily on attentional resources, it should be negatively affected to a greater degree by cognitive load than less resource intensive or automatic processes. In other words, a task requiring memory for binding should suffer more than a task requiring only memory for individual features under divided attention conditions if binding is an attentionally demanding process.

Following this logic, Allen, Baddeley and Hitch (2006) assessed memory for single features (e.g., colour and shape) and memory for bindings between these features under full and divided attention conditions. Each trial consisted of an array of four items (outline shapes in the 'remember shapes' condition; coloured squares in the 'remember colours' condition; coloured shapes in the 'remember bindings' condition) with explicit instructions in each experimental block to remember each single feature (the 'remember shapes' and 'remember colours' conditions) or the conjunctions of colours and shapes (the 'remember bindings' condition). The array would be followed by a short delay and finally a single probe stimulus consisting of either an object that was seen in the preceding array or a new object (with the nature of the object depending on the condition being undertaken). The task was to identify whether or not this probe stimulus occurred in the preceding array. Single feature probes would consist of either a feature that was present in the preceding array or a feature that was new (not present); and conjunction probes would be either a conjunction seen in the array or a new combination of seen features (i.e., the bindings switched over).

In their Experiment 2, the task was completed under high cognitive load (e.g. counting backwards in threes) and low cognitive load (e.g. repeating a number aloud, serving as concurrent articulation). Allen et al. (2006) found that memory for bindings between surface features was not disrupted any more by the addition of a concurrent load than memory for individual features, suggesting that surface feature binding proceeds relatively automatically in VSTM (or rather, draws on no more attentional resources than feature memory). This finding was inconsistent with the idea that feature binding must take place in a multimodel episodic buffer that draws on domain general attentional resources (Baddeley, 2000; Baddeley, Allen & Hitch, 2011), at least as far as the binding of surface features is concerned (see Chapter 3 for evidence relating to location binding).

However, a later study by Brown and Brockmole (2010) contradicted this finding. Following the same basic paradigm as Allen et al. (2006), Brown and Brockmole (2010; Experiment 2) tested whether surface-feature binding is resource demanding by utilising a serial presentation procedure to manipulate attentional load. By presenting each object one at a time, participants were required to hold each object in memory until the probe was presented, increasing the attentional demands. Their experiment showed that remembering the bindings between features was disproportionately affected by this manipulation compared to memory for single features, suggesting that surface-feature binding may be a resource demanding process. In an effort to resolve these contradictory findings, Allen, Hitch, Mate, and Baddeley (2012) further investigated the effects of a concurrent demanding task on memory for colours, shapes, and combinations of these features by testing key differences between those two studies. These included firstly, the duration of the attentionally demanding backward counting task. Brown & Brockmole (2010) required that the participant continued this backward counting from presentation of the array, until a button is pressed registering the participant's judgement of the probe, while Allen et al. (2006) only required counting to continue during presentation of the initial array and during the delay, but counting was to be ceased once the probe item was displayed. This led to the possibility that it was specifically recall of the bound combinations that was disproportionately affected by the backward counting, and not the binding process at encoding; As such, Allen et al. (2012) used backward counting until a decision had been made, in line with Brown and Brockmole (2010). Additionally, Brown and Brockmole (2010) presented their array for 900ms, considerably longer than the 250ms used by Allen et al. (2006). This pushed memory for the single feature of colour to near ceiling, and with memory for shape, and for colour and shape conjunctions, consistently shown to be poorer than memory for colour alone (e.g. Allen et al., 2006; Brown & Brockmole, 2010; Song & Jiang, 2006; Wheeler & Treisman, 2002). This increased presentation time, combined with smaller arrays of three objects (as opposed to four in Allen et al., 2006) may have artificially created an apparent interaction through effectively boosting single feature memory performance. To address this, Allen et al., (2012) used a consistent array presentation time of 1000ms, and tested set sizes of both three and four. Their findings indicated that even taking differences between the studies of Allen et al. (2006) and Brown and Brockmole (2010) in to account, surface-feature binding was not disrupted by the addition of a concurrent load task.

This again supports the assertion that surface feature binding occurs relatively automatically in VSTM and the authors suggested that perhaps surface-feature binding occurs in-house in the visuo-spatial sketchpad, perhaps as a result of earlier perceptual processing. These already bound features may then be fed through to the episodic buffer. Furthermore, while Brown and Brockmole (2010; discussed in depth later in this chapter), initially appeared to provide some evidence that surface feature binding may be specifically affected by an attentionally demanding secondary task, Allen et al. (2012) proposed that these findings may be accounted for by a difference in the statistics used to measure performance. While Allen et al. (2006) used d' as a measure of signal detection, Brown and Brockmole (2010) instead used A'. While these signal detection measures elucidate main effects in a manner consistent with one another, Allen et al., (2012) argued that A' appears to over-estimate the presence of an interaction giving rise to the observation of a specific decline in feature binding performance under higher cognitive load in this change detection task. In sum, the majority of studies using the cognitive load method appear to converge in their findings that surface-feature bindings are stored in memory using no more cognitive effort than memory for single features, supporting the contention that this type of binding may proceed relatively automatically in VSTM (Allen et al., 2012). Further evidence for this idea can be found by examining studies that have examined suffix effects in the context of binding memory, discussed in detail below.

1.3.3 The role of cognitive effort in surface-feature binding in VSTM: Suffix Effects

An alternative method to demonstrate whether surface feature binding is a resource demanding process is the investigation of suffix effects. Studies that have used this method follow the same basic change detection task paradigm described above, but this time present an additional object during the retention interval (the time elapsed between the presentation of the to-be-remembered array and the test item). The role of this object is to test whether memory for single features, or bindings (which are often argued to be fairly fragile) can be disrupted by showing a task irrelevant object in between. The suffix is used to demonstrate (1) whether objects held in memory are interfered with, or overwritten, intentionally, and (2) whether this can happen incidentally through processing the suffix object, in-spite of it being an object participants are specifically instructed to ignore. Ueno, Mate, Allen, Hitch, and Baddeley (2011a) and Ueno, Allen, Baddeley, Hitch, and Saito (2011b) investigating the effects of a visual suffix on the binding between surface-features (colour and shape). The experiments utilised either a suffix object consisting of features not part of the stimulus set (implausible suffix), or used a suffix that consisted of features that are task relevant, but were not shown in the array on that specific trial (plausible suffix). In Experiments 1 and 2, when a plausible suffix was displayed, performance was more adversely affected than when an implausible suffix was displayed. This points to the notion that attention is drawn more to features that are part of the stimulus set, suggesting that filtering plausible information is more resource demanding than a general information filter, hence bindings are specifically affected by a plausible suffix.

Ueno et al. (2011a) Experiment 3 showed that this suffix effect extended to 'semi-plausible' suffixes: when a suffix consisted of one feature that was part of the experimental set, and one feature that was never part of the experimental set, the effect was equivalent to that of the effect of the plausible suffix in their Experiments 1 and 2 (Ueno et al., 2011a). This provides evidence that there is an attentional filter in visual short-term memory that operates on a feature level; and when a feature is allowed to pass through that filter, the original object held in memory is over-written. Ueno et al. (2011b) built on this study through the addition of a semi-plausible suffix; a suffix that consists of one plausible feature, that formed part of the stimulus set for this experiment, and one implausible feature, a feature that was not part of the stimulus set for this experiment. This variation of the paradigm investigated whether memory for surface-feature binding (colours and shapes) was more greatly affected than single feature memory by plausible, implausible, or semi-plausible suffixes. It was shown that memory for bound conjunctions of surface-features was affected to the same extent by all classes of suffix, adding to the notion that the encoding of bound conjunctions of surface features occurs automatically. In sum, this sequence of studies (Allen et al., 2006; Allen et al., 2012; Ueno et al., 2011a, 2011b) shows that surface-feature binding proceeds without any more cognitive effort than that required to remember single features.

1.3.4 Cognitive effort in surface-feature binding in VSTM: Preliminary conclusions

Based on existing evidence it would appear, that surface-feature binding largely occurs automatically (that is to say, with no more effort than that required to support memory for individual features) in VSTM. Increasing task difficulty through increased set sizes has little detrimental impact on feature binding performance (Oberauer & Eichenberger, 2013; Wheeler & Triesman, 2002) and adding a cognitive load similarly has no clear impact on memory for bound combinations of features (Allen et al., 2006; Allen et al., 2012). Finally, the extra cognitive load created by the addition of a suffix (additional stimulus that appeared during the interval between the presentation of the to-be-remembered array and the memory probe) has no impact on surface-feature binding beyond that which is also observed for single feature memory when the suffix contains one or more implausible features (features that did not appear as part of the preceding array; Ueno et al., 2011a, 2011b). Note however, that when the suffix was plausible (constructed from features that were present in the preceding array, there was a demonstrable reduction in task accuracy). While it seems that surface-feature binding proceeds relatively automatically (cf. plausible suffix; Ueno et al., 2011a, 2011b) there is evidence to suggest that location binding may in fact be a separate process and there is suggestion that location binding could be a cognitively demanding process (e.g. Elsley & Parmentier, 2009). This is discussed in detail in the section below.

1.4 Location binding in VSTM

Support for the contention that surface-feature binding and location binding may diverge in their mechanistic underpinnings can be inferred from existing studies of cognitive ageing. For example, older adults appear to exhibit failures for memory for objects in locations (location bindings: Cowan et al., 2006; Mitchell et al., 2000) while memory based on correct combinations of surface features appears to be relatively preserved (Brown & Brockmole, 2010). There are (at least) two possibilities for this potential specific decline in older adult location binding performance. First, it might be underpinned by age-related decline in memory for contextual information (Kessels, Hobbel & Postma, 2007), perhaps caused by hippocampal deterioration (Lupien et al., 1998); and second, it may be a consequence of a general decline in attentional functioning in older age, which may relate to changes in executive functioning (see Verhaeghen & Basak, 2005 for evidence relating to task switching). This attentional decline could, potentially, leave surface-feature binding ability intact (as a process thought to occur relatively automatically; (Allen et al., 2006, 2012; Oberauer & Eichenberger, 2013; Wheeler & Triesman, 2002)), while causing a deficit in a more attentionally demanding location binding process (e.g. Elsley & Parmentier, 2009). Thus, although existing literature on binding in VSTM and normal cognitive ageing is relatively sparse, there is a potential link to findings pertaining to cognitive load. The role of attention during location binding is discussed in detail below.

1.4.1 Cognitive effort in location binding: Incidental encoding and binding asymmetry

While evidence relating to the role of cognitive effort in surface-feature binding is relatively clear-cut in suggesting that this type of binding proceeds relatively automatically (Allen et al., 2006, 2012; Oberauer & Eichenberger, 2013; Wheeler & Triesman, 2002), studies examining the role of cognitive effort during location binding have yielded mixed findings. More specifically, studies that have assessed the binding between objects and their locations under incidental encoding instructions (i.e., the object only is task relevant, but the impact of moving the object to a new location on object memory is assessed) would appear to provide evidence that this type of binding occurs automatically (to the extent that it occurs in spite of task instructions). Olson and Marshuetz (2005) demonstrated that objects are incidentally bound to their locations on the basis of nearby contextual information. Their task (in Experiment 1) required participants to remember the identity of only a single object, with this object placed on a background consisting of a white square with a larger grey square. While the difficulty of this task is obviously low, rendering accuracy measurements uninformative, response latency measurements revealed interesting insights in terms of how objects are tied to their locations. During test, the array object was displayed in one of the four corners of the white square, which itself was placed in one of the four quadrants of the larger grey square. This gave rise to three conditions in the probe display; (1) no change, where the probe display was identical to the array; (2) global change, where the object remained in the same corner of the white square as in the array but the white square was relocated to a different quadrant of the grey square; and (3) local change, the object moves to a different corner of the white square, and the white square was relocated to a different quadrant of the grey square. Response latencies were similar in the no change, and global change condition, but markedly longer for the local change condition. This indicates that objects were incidentally bound to their location on the basis of nearby contextual features, here consisting of the white square, as opposed to their absolute location in space. While further experiments produced insights into which objects can used to provide nearby contextual location information, the crucial finding for this section was the demonstration that objects are incidentally bound to their location.

More recently, Keizer, Hommel, and Lamme (2015) investigated the binding of Gabor patches (a sinusoidal grating; essentially a patch of alternating black and white lines with the lines on each patch varying in width, frequency, and orientation) to locations. In their task, on each trial, two Gabor patches were presented sequentially with two possible locations and two possible orientations (vertical or horizontal) and each was preceded and trailed by visual masks. In half of the trials, in the presentation of the first Gabor patch (S1) there was a 100ms gap between the mask presentation and the patch presentation, making the patch clearly visible (ineffective masking), and in the other half of trials there was no gap which is claimed to render the patch not consciously visible (effective masking). This was followed by the presentation of the second patch (S2). Participants responded to the orientation of the second patch with the task of identifying the direction of the orientation, and under ineffective masking showed slower response latency when the orientation of the object changed but the location remained the same between S1 and S2, but under effective masking showed slower response latency when the location changed but the orientation remained the same between S1 and S2; both indications of bindings between orientation and location. Overall then, irrespective of whether the participant was consciously aware of the presentation of a patch, at test there was evidence that the orientation was bound to the location in which it was presented. This evidence that location binding may have occurred without conscious awareness of course lends itself to the notion that the binding between the orientation of an object and the location of that object proceeds relatively automatically in working memory. Further evidence for incidental binding can be found from the studies that have examined binding symmetry, discussed in detail below.

More evidence for incidental bindings between objects and their locations comes from studies that have aimed to assess binding symmetry. Studies on this issue assess whether incidental binding occurs symmetrically (that is, regardless of which feature (object or location) is task relevant) or whether it is asymmetrical (that is, incidental binding only occurs when the object is task relevant but not when the location is task relevant). Investigating this, Campo et al. (2010) utilised a paradigm designed to specifically assess the incidental binding of letters to locations, and of locations to letters, in younger adults. Participants were shown arrays of four letters in distinct locations and were tasked with either remembering either just the letters (the locations were task-irrelevant) or just the locations (with the letters being task irrelevant) that were present in the display, then to judge a single probe item in terms of whether it contained a seen before feature or not. The key comparison, indicative of binding, was between two probe types: *intact probes* consisting of a letter presented in its original location (i.e., the bindings were preserved between display and test); and *recombined probes* where the probe letter was present in the array but appeared in a location occupied by a different letter (i.e., the bindings were switched). Binding in this task predicts superior performance for intact probes (where the bindings were preserved) relative to recombined condition (where the bindings were switched over). A 'binding asymmetry' was found, whereby evidence of binding was observed in the attend letters task, but not in the attend locations task. Elsley and Parmentier (2015) extended this study in adaptation of the paradigm that investigated the longevity of 'binding asymmetry' using verbal-spatial features. With the additional factor of variable delay times between memory array and test, Elsley and Parmentier (2015) demonstrated that bindings between letters and their locations persisted for 15 seconds. When tasked with remembering locations, participants again demonstrated that location memory can be accessed independently from object memory with no evidence of poorer performance when bindings were switched. Thus, as in Campo et al. (2010) the participants showed a 'binding asymmetry' with evidence of binding in the attend letters task but not the attend locations task, and provided crucial evidence of the strength of these bindings with them persisting over a remarkably long period of time.

In short, this binding asymmetry is suggestive of the notion that location may hold some kind of special status amongst feature types. Surface features, in this case letters, were bound to locations despite this not being relevant to the task at hand. However, when location was task relevant the two features were not bound, suggesting that objects require, or at least benefit from in some way, a binding with their location, while the inverse is not true; essentially, objects require a location, locations do not require an object. The question to what extent this is an automatic process, or whether it is effortful, remains unaddressed.

1.4.2 Cognitive effort in location binding: Cognitive load

While evidence from studies of binding (a)symmetry suggest that location binding occurs automatically, they only do so indirectly and to the extent that they show binding occurring regardless of task instructions. They have not explicitly tested whether this process is effortful. Indeed, there are studies that suggest location binding may be an effortful process. For example, Prabhakaran, Narayanan, Zhao and Gabrieli (2000), used a task that required participants to remember both verbal and spatial information, then respond positively to probes that contained one, or both features, and negatively to probes that contained two features not seen in the preceding array. They demonstrated that the prefrontal cortex showed greater activation for integrated representations than for unintegrated information, while posterior regions showed greater activity for unintegrated information than for integrated representations. With the dorsolateral prefrontal cortex consistently shown to be part of a network important for the control of attention (Goldman-Rakic, 1987; Kane & Engle, 2002) these findings may suggest that binding, at least between verbal and spatial features, may require attention. More direct support for this contention came from a study by Elsley and Parmentier (2009) who, using a task adapted from Prabakaran et al. (2000), demonstrated that the binding of letters to locations was reduced by a concurrent cognitive load task. Participants were tasked with remembering the identity and location of four letters, though not their combinations. At test, participants were required to respond 'yes' when both the letter and the location matched that shown in the previous array, irrespective of their initial bindings. The probe consisted of a single letter, with the key comparison made between probes where the letter appeared in its original location (an intact probe), and probes where the letter appeared in a location that previously contained a different letter (a recombined probe). Under lower cognitive load, performance was poorer in response to recombined probes than intact probes providing evidence that features had been bound together into integrated representations. However, higher cognitive load reduced the intact/recombined probe difference, suggesting that the binding of letters to locations apparent under low cognitive load, draws upon attentional resources.

1.4.3 Cognitive effort and location binding in VSTM: Preliminary conclusions

In sum, existing literature would appear to support the contention that surface-feature binding and location binding diverge in their attentional requirement with the latter but not the former requiring cognitive effort. However, conclusions here are limited by the fact that experimental paradigms used across tasks assessing binding and attention across binding types have been based on different measures of binding (e.g., Allen et al., 2006 used the comparison between memory for individual features and memory for bindings while Elsley & Parmentier, 2009 used the comparison between intact and recombined probes). Additionally, both Elsley and Parmentier (2009) and Prabharakran et al. (2000) examined verbal-spatial (rather than visual-spatial) feature binding – it is possible this represents a special case of location binding, given the reliance on tying letters to locations in everyday life (see Elsley & Parmentier, 2015, for further exploration of this). Thus an opportunity exists to contrast surface-feature binding and location binding in VSTM within a single paradigm in the presence and absence of a cognitive load. This issue is addressed in Chapter 2. The evidence presented above suggesting that surface-feature binding and location binding diverge in their attentional requirement relates to a more general contention that the two types of binding may have distinct mechanistic underpinnings. Further evidence for this contention can be found by examining studies of feature binding and cognitive ageing, discussed in detail in Chapters 2 and 3. Below we present a discussion of methodological differences between existing studies of binding.

1.5 Issues with methodological differences: Intentional vs incidental binding

As it stands, evidence regarding the nature of both general processing and attentional requirements for surface-feature binding and location binding come from vastly different paradigms. These paradigms typically fall into two distinct categories: those that explicitly instruct memory for bindings - intentional binding paradigms (e.g. Allen et al., 2006; Allen et al., 2011; Brown & Brockmole, 2010; Ueno et al., 2011a; 2011b), and those that assess whether binding has occurred in spite of no explicit instruction to do so - incidental binding paradigms (e.g. Campo et al., 2010, Elsley & Parmentier, 2009; 2015; Olson & Marshuetz, 2005). This key methodological difference may be at the heart of differences noted in terms of the attentional requirement of surface-feature binding and location binding. While Allen et al. (2006) found no evidence that surface-feature binding requires attentional resources beyond that required for single feature memory, other studies (Incidental: Keizer et al., 2015; Intentional; Elsley & Parmentier, 2009) are more mixed as to whether incidental location binding is cognitively demanding. Critically, while it may appear that binding type (surface-feature or location binding) drives whether or not the binding process requires cognitive effort, existing studies leave open the possibility that it is instead the method of binding assessment (intentional or incidental encoding instructions) that explains the differences observed. Accordingly, one aim of the current thesis is to contrast location binding and surface-feature binding using only the intentional binding paradigm developed by Allen et al. (2006). This issue forms the basis of Chapter 2. Further evidence relating to both the issue of the attentional requirement for binding and differences in binding type can be found in the ageing literature, discussed in detail below.

1.6 Ageing, Working Memory, and Binding

The investigation of many cognitive processes is furthered by studying specialist populations where the processes in question appear to no longer operate as they do in early adulthood; feature binding is one such area. While there is a large body of research investigating age-related deficits in associative learning in long-term memory (requiring the creation and retrieval of links between single units of information: see The Associative Deficit Hypothesis, Naveh-Benjamin, 2000), there are relatively fewer studies assessing the integration of visuo-spatial features in VSTM. Of the studies that have been conducted, there is evidence to suggest that perhaps older adults may be specifically impaired during location binding (Cowan et al., 2006; Kessels, Hobbel and Postma (2007), while surface-feature binding may be relatively spared (Brockmole, Parra, Della Sala, & Logie, 2008; Brown & Brockmole, 2010; Parra, Abrahams, Logie & Della Sala, 2009). Beyond this, there is mixed evidence to suggest that older adult memory decline may relate to poor attentional functioning (Rabinowitz, Craik, & Ackerman, 1982; Verhaeghen & Basak, 2005).

It is well defined that memory declines in advancing age (e.g. Kausler, 1994), and this is particularly true of working memory. Salthouse, Mitchell, Skovronek, and Babcock (1989) demonstrated that older adults' task performance are more greatly affected than younger adults when task complexity is increased, consistent with the notion of reduced working memory capacity. Alongside a general decline in working memory processing, and in attention (Rabinowitz, Craik, & Ackerman, 1982), ageing has been shown to differentially impact different types of working memory tasks (Johnson, Logie, & Brockmole, 2010). For example, Johnson et al., (2010) suggest that variance in feature binding task performance was explained by age group to a far greater extent than digit span or spatial orientation tasks. This suggests that feature binding processes could be specifically impaired as a consequence of healthy ageing, in spite of relatively intact memory for single features. Of the few studies that do exist, older adults appear to exhibit failures of memory for objects in locations (location bindings: Cowan et al., 2006; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000), while memory based on correct combinations of surface-features appears to be relatively preserved (Brown & Brockmole, 2010).

There are (at least) two possible explanations for this potential specific decline in older adult location binding performance. First, it might be underpinned by age-related decline in memory for contextual information (Kessels, Hobbel & Postma, 2007), perhaps caused by hippocampal deterioration (De Leon et al., 1997; Jack et al., 2000; Lupien et al., 1998); and second, it may be a consequence of a general decline in attentional functioning in older age, which may relate to changes in executive functioning (see Verhaeghen & Basak, 2005 for evidence relating to task switching; discussed in more depth in the next section). Thus, there is a potential link between binding that deteriorates alongside healthy ageing and a general decline in attentional functioning. We begin below with an overview of surface-feature binding and ageing before discussing evidence for location binding and ageing.

1.6.2 The binding of surface-features in VSTM: Cognitive Ageing

A number of recent studies suggest that the binding of surface-features in VSTM is relatively unimpaired in older adults (Brockmole, Parra, Della Sala, & Logie, 2008; Brown & Brockmole, 2010; Isella, Molteni, Mapelli, & Ferrarese, 2015; Pertzov, Heider, Liang, & Husain, 2015; Olson, Page, Moore, Chatterjee, & Verfaellie, 2004; Parra, Abrahams, Logie & Della Sala, 2009; Rhodes, Parra, & Logie, 2016; cf. Chen & Naveh-Benjamin, 2012). For example, Parra, Abrahams, Logie, and Della Sala (2009) tested older and younger adults on change detection ability in arrays of single coloured (e.g. a square block of colour) and bi-coloured objects (e.g. a square block of colour within a larger square of a different colour). Their Experiment 1 showed that both younger and older adults performed more poorly in detecting changes between memory array and test when faced with bi-coloured objects rather than single coloured objects, in line with the suggestion that working memory capacity should be measured both within feature dimensions and in terms of bound combinations. Critically, this finding suggests that surface-feature binding is no more impacted by the effects of healthy ageing than memory for single features. A second experiment replicated the task but this time sought to increase task demands by using arrays consisting of four objects rather than the three object arrays used in their Experiment 1. Older adults were no more affected by the increased set size than younger adults, suggesting that surface feature binding performance was relatively preserved in the older adult sample.

Brockmole, Parra, Della Sala, and Logie, (2008) focused on whether the general decline of visual working memory that occurs as a function of healthy ageing can be explained by feature binding deficits. The study began by investigating whether number of features or number of objects, is the limiting factor in older adult visual memory through the use of a simple change detection task (Experiment 1). Participants were shown an array of objects that varied in set-size between two, four, or six coloured shapes. The experiment showed a general decline in performance with older adults showing poorer memory for both single features and conjunctions of features, but no specific decline in memory for either task relative to younger adults. Experiment 2 used consistent set sizes of four and six objects, to investigate single feature memory (colour, or shape) and feature conjunction memory (combinations of colour and shape) across younger and older adults. As is commonly found, younger adults performed better on the task assessing memory for colours than for shapes, and better for shapes than for conjunctions. Older adults here, at first glance appeared to exhibit a specific binding deficit. However, this was in fact driven by poorer memory for shapes as a single feature rather than for conjunctions in particular. Finally, in their Experiment 3 they investigated the impact of varying the delay time between array and test. Again the increased delay time in Experiment 3 caused, in older adults, a small reduction of performance where memory for conjunctions of colour and shape were required but crucially did not result in performance markedly poorer than that exhibited by younger adults. Thus, older adults showed a general decline in visual memory; a decline that was not specific to the creation and storage of bound feature combinations.

Building on this finding of a general decline in visual memory as a function ageing, Brown and Brockmole (2010) used a paradigm similar to Allen et al. (2006) where younger and older adults were required to commit to memory an array of coloured shapes under instruction to remember colours only, shapes only, or the conjunction of colour and shape features. A single probe item presented in a neutral location was then responded to on the basis of whether it was present in the array or not (this probe item consisted of only the task relevant feature; e.g. a blob of colour in the colour only condition, a shape with no colour fill where the task required memory of only the shape, a coloured shape where the probe was testing memory for conjunctions between colour and shape). Brown and Brockmole (2010, Experiment 1) showed that for both younger and older adults, memory was slightly worse for conjunctions than for single features, but that no specific deficit was present for binding in the older adult sample. In addition, in the same experiment younger and older adult performance was assessed under low cognitive load (repeating a two digit number aloud) and high cognitive load (counting backwards in threes from a two digit number given at the start of each trial). The rationale of this comparison was that under high cognitive load, younger adults' performance may mimic that of older adults if older adult performance suffers as a consequence of reduced attentional resources. The findings suggested that both age groups performed more poorly under high cognitive load in both the single feature and feature binding conditions, but there was no specific detrimental effect of cognitive load on binding, and no evidence of impaired binding performance in the older adult sample. This finding suggests that binding both draws no more heavily on attentional resources in working memory than memory for single features, and is unaffected by healthy cognitive ageing. Interestingly, their Experiment 2 showed a specific deficit in surface-feature binding ability in older adults albeit with sequential rather than simultaneous stimulus presentation. By presenting the to-be-remembered objects one at a time, rather than showing them on-screen all at once, this experiment increased memory load. Under these conditions, older adults elicited markedly poorer performance in conditions requiring memory for conjunctions of features, compared to conditions where only individual feature memory was required; a difference that was not present for younger adults who, although performing poorer than when objects were presented simultaneously, show no specific impact of the additional memory load in the conjunctions condition. In sum, although older adults show poorer performance in a simple change detection tasks overall, the reduction in accuracy relative to younger adults was comparable for single visual features and for conjunctions of those features indicating that memory for bound combinations of surface-features was no more disrupted than memory for single features by cognitive ageing.

In order to assess the discrepant findings in Brown and Brockmole's (2010) study further, Brown, Niven, Logie, Rhodes, and Allen (2016) used the same basic paradigm as Allen et al., (2006) to investigate the effect of ageing on memory for bound combinations of surface features under conditions of varied encoding time (Experiment 1), simultaneous vs. sequential presentation (Experiment 2), and suffix interference effects (Experiment 3). Each experiment compared memory for single features (colour, shape) with memory for bound combinations of colour and shape. Experiment 1 contrasted presentation times of 900ms and 1500ms investigating the issue of a decline in processing speed in healthy ageing, under the premise that older adult processing speed may simply be longer than younger adults (e.g. Salthouse, 1996). As such, allowing older adults longer to process the objects on display may alleviate any difference between younger and older adults by addressing the slower processing speed. While younger adults showed no impact of the shorter presentation time on their feature binding performance, older adults elicited poorer performance in the feature binding condition, compared with performance in the shapes only condition (the more difficult of the single feature memory conditions) in line with the suggestion that some of the older adult deficits in working memory tasks may be driven by slower processing speed. Overall then, although older adults consistently showed poorer memory for feature bindings relative to single features in all three conditions, this was analogous to younger adults who also showed negative effects of sequential presentation, and of suffix interference, in their memory for bound feature combinations. Thus, Brown et al. (2016) conclude that there is no visual binding deficit as a function of healthy ageing. Although older adults appear unimpaired during surface-feature binding tasks, there is evidence to suggest their location binding performance is worse than that of their younger counterparts (e.g., Cowan et al., 2006; Mitchell, Johnson, Raye, Mather and D'Esposito, 2000). This issue is discussed in detail below.

1.6.3 Location binding in VSTM: Cognitive Ageing

While surface-feature binding performance appears to be relatively preserved in older adults, a number of studies suggest that location binding performance deteriorates with age. For example, Mitchell, Johnson, Raye, Mather and D'Esposito (2000) tested younger and older adults on their memory for objects, locations, and combinations of object and location. Three objects were presented in a serial fashion, each in a unique location with participants focusing on which ever of the memory conditions was cued at the start of the trial (object identity, location identity, object & location combination). The probe consisted only of the to-be-remembered item (the object in an unused location, a mark indicating the location, or the object in a location). For both younger and older adults, performance was near identical for object memory and location memory. However, when comparing these single feature conditions with the combination condition, older adults produced a greater proportion of false alarms relative to hits when compared to younger adults, thus illustrating a deficit in their ability to bind objects to locations. Further to the findings of Mitchell et al. (2000), Cowan et al. (2006) presented participants with arrays of four coloured squares, followed by a second array either identical to the first or with one colour different. Participants were then cued to look at one square and identify whether this one square was the same in the preceding array. The trials tested either memory for colours (i.e. when the cued square in the probe array was changed, it changed to a colour that was not in the initial array) or memory for bindings (i.e. when the cued square in the probe array was changed, it changed to a colour that was present elsewhere in the initial array, constituting a test of location binding – i.e., the bindings switch over). Older adults were found to be specifically impaired in the binding condition relative to the performance of younger adults perhaps suggesting that older adults may exhibit a specific decline in location binding performance relative to younger adults. However, it should be noted that this apparent decline in the older adult group could also be explained by older adults' lower sensitivity in detecting changes that are small in magnitude (see Kline, Schieber, Abusamra, & Coyne, 1983, for a description of how ageing affects visual sensitivity).

Given the existing evidence of older adults' apparent failings in incidental binding (e.g. Kensinger, Piguet, Krendl & Corkin, 2005), a logical avenue for the exploration of the effects of ageing on binding performance is that of the binding asymmetry evaluated by studies described above (Cowan et al., 2010; Elsley & Parmentier, 2015). A uniform decline in the ability to incidentally encode information secondary to the task is apparent in advanced age (e.g. Naveh-Benjamin et al., 2009; Verhaeghen and Basak, 2005). Testing long-term memory, Naveh-Benjamin et al. (2009) tested younger and older adults in their memory for pairings of names and faces. Under explicit instructions to remember which name was paired with which face, each age group performed to a similar level. Under incidental encoding instructions (where participants were asked for subjective judgements of whether the name and face 'fit' together, rather than being instructed to remember the pairings), older adults performed significantly worse than younger adults on memory for these incidentally bound pairings indicating a clear impairment of incidental encoding of the relationships between names and faces. Much like Mitchell et al. (2000) this difference was driven by higher false alarm rates (responding 'yes' to a probe when the correct answer is 'no'). More pressing for this thesis, is how this apparent age related impairment in memory for incidental information, occurs in short term memory.

As mentioned briefly above (section 1.6.2) a key component of this decline may be the application or availability of attentional resources. For example, Cowan et al. (2006) observed that older adults tended to make errors when the more subtle binding changes were made in mixed task conditions where a degree of task switching was required, perhaps suggesting that attention was strained and so errors were made. Verhaeghen and Basak (2005) provided evidence supporting this idea using a modification of the n-back task. In a typical n-back task participants must remember a sequence of stimuli (for example, letters) and judge whether the present stimulus matches the stimulus shown *n* trials earlier, with *n* typically varying from one to five. As such the task requires participants to hold sequences of stimuli in memory and update these sequences as the task proceeds (see Kirchner, 1958, for the classic example of this task in relation to age differences). Verhaeghen and Basak's (2005) findings largely showed that a switch in focus from remembering one trial back to remembering two or more trials back more adversely affected older adults than younger adults once the general slowing of older adult responses was statistically accounted for. Thus, in line with Cowan et al. (2006), these results suggest that an increase in the complexity of task demands affects older adult performance to a greater degree than it affects younger adult performance, supporting the position that older adults exhibit a general decline in attentional functioning. We refer to the position that impaired performance in older adults on binding tasks is due to a decline in attentional functioning as the *ageing-attention* hypothesis. Under this hypothesis, older adults should be impaired on any binding task shown to recruit attentional resources. This issue is assessed in Chapters 2 and 3.

In contrast, rather than an artefact of a general decline in attentional capacity, the specific pattern of performance decline in older adults may be due to failings in a more specific mechanism – that concerned with the representation of contextual information (the location of items provides a key example of a contextual feature). Kessels, Hobbel and Postma (2007) assessed this notion with a change detection task testing object memory, location memory and memory for the combination of object and location in younger and older adults. The task here required participants to remember the relevant feature (or combination) of a set of seven objects then identify which objects were seen from a set of 30 (objects only), which grid locations were occupied by a black cross (locations only) and where on the grid seven items had appeared (combination task). Although older adult performance was comparable to that of younger adults in the objects only and location only conditions, older adults exhibited performance indicative of a specific decline in the binding of objects to contextual information with markedly poorer performance in the combination condition. This demonstrates that a decline in location binding performance may be a facet of normal cognitive ageing and the authors linked this decline to a specific mechanism relating to contextual information.

More recently, Meulenbroek et al. (2010) showed that while younger adults use contextual information from the environment as cues to aid recall of object-location pairings, older adults do not, relying instead on pure stimulus response associations. Evidence from fMRI showed that older adults were recruiting declarative memory processing to address the demands of the task while younger adults used more posterior regions believed to be related to the recruitment of imagery. This again suggests that older adults are reliant on memory for just the feature or object required to complete a task to the detriment of memory for additional information, implying that older adults would not bind objects to locations unless specifically instructed to do so. We refer to the position that older adults should be specifically impaired on tasks requiring location binding, (but not surface-feature binding) as the *ageing-context* hypothesis, under which we should see a reduction in binding performance in older adults in circumstances when contextual information forms a feature of the binding task.

1.6.4. Older adults and binding: Conclusions

The evidence thus far points towards a specific location binding deficit in advanced age (e.g. Cowan et al., 2006) explainable in terms of impaired processing of contextual information (Meulenbrock et al., 2010) or in terms of reduced attentional resources (Cowan et al., 2006; Verhaeghen & Basak, 2005). At the same time, there exists evidence that unlike location binding, surface-feature binding remains relatively intact in those that have experienced healthy ageing (Brown & Brockmole, 2010). That these findings have come to light using notably different experimental paradigms leaves the question of whether the different performance shown in each type of binding (location binding versus surface-feautre binding) are a facet of ageing, or of the methods employed to investigate them. In addition, the question of what may cause these differences remains unsolved. Thus, a first logical step in untangling these mixed findings is to investigate the ageing-attention hypothesis, and the ageing-context hypothesis by contrasting surface-feature binding and location binding in a single paradigm; this forms the basis of Chapter 2. Beyond this, older adults' apparent failings in respect of incidental encoding provide a tantalising route for further investigation of feature binding and ageing, with this providing the focus for Chapters 3 and 4.

1.7 Summary and empirical aims of the present thesis

This thesis aims to contrast the *ageing-attention* hypothesis with the *ageing-context* hypothesis. To this end, Chapter 2 assessed location binding and surface-feature binding performance across younger and older adults (Experiments 1 & 5). The results of Experiments 1 and 5 were compared with the results from Experiments 2, 3, and 4, which assessed the attentional requirement for surface-feature binding and location binding in younger adults.

Additional to the aims of Chapter 2, there is a further possible explanation for differences observed between studies investigating the attentional requirement for surface-feature binding and location binding. While experiments of the type utilised by Allen et al. (2006) and Brown and Brockmole (2010) investigate *explicit* feature binding of surface-features (that is, where memory for combinations of colours and shapes is explicitly required in order to complete the test), the location binding studies of Prabhakaran et al. (2000) in addition to Elsley and Parmentier (2009) were slightly different in that participants were required to respond as to whether verbal and spatial features had been present in the array, *regardless* of their initial pairings. Consequently, explicit memory for the bindings was not a task requirement. This distinction between incidental and explicit binding could potentially drive the different results observed across existing studies. Therefore, Chapter 3 uses an incidental binding paradigm, of the type used by Campo et al. (2010), to contrast the performance of younger and older adults in verbal-spatial binding (Experiment 6) and visual-spatial binding (Experiment 7), in addition to assessing the role of attention (and whether this can be used to explain the performance of older adults) in incidental visual-spatial binding (Experiment 8). The final empirical section, Chapter 4, further investigates the *ageing-context* hypothesis using an adapted form of Olson and Marshuetz's (2005) incidental binding paradigm to assess whether older and younger adults address the binding tasks used in Chapter 3 in, cognitively, the same manner. Chapter 5 presents a compiled discussion of the key findings from the empirical chapters.

Chapter Two. Binding Performance: Ageing and Attentional Requirement.

2. Binding Performance: Ageing and Attentional Requirement.

2.1 Introduction

The experiments in Chapter 2 investigate the extent to which surface-feature binding abilities and location binding abilities decline differentially with age (Experiments 1 & 5); and the extent to which this decline could be explained by a specific deficit in either attention (Experiments 2-4), or in context memory (Experiments 1 & 5). Previous studies have shown that surface-feature binding performance may be relatively preserved in older adults. For example Brown and Brockmole (2010) used a paradigm based on that developed by Allen et al. (2006) comparing memory for single features (colour, shape) with memory for bound combinations of those features, between younger and older adult participants. Memory for bindings was measured by comparing performance in the bound combinations condition with performance in the more difficult of the two single feature conditions (typically shown to be the 'shape' condition in studies of this kind; e.g. Allen et al., 2006). In Brown and Brockmole's (2010) study, younger and older adults were shown to be able to accurately recall bound combinations with little deficit in accuracy compared with memory for shapes alone. This experiment therefore indicates that older adults' surface-feature binding ability remains relatively intact during normal cognitive ageing. Location binding performance however, appears impaired in older adults. Cowan et al. (2006) used a paradigm similar to the single change detection paradigm developed by Luck and Vogel (1997) where on each trial, a test array of coloured squares was presented, then after a short delay (during which the screen was blank), a second array appeared with one square cued. The participants had to identify whether the cued square had changed colour between the memory and test arrays. It was found that older adult participants tended to perform worse in trials where two squares swapped colours between memory and test indicating a potential issue in location binding performance (in other words, older adult performance suffered where the cued square swapped colour with another square in the array so that the bindings between colours and locations were switched over; see also Mitchell et al., 2000).

These findings are, however, based upon comparisons drawn across very different experimental paradigms. Experiment 1 of this thesis therefore aimed to directly compare surface-feature and location binding in younger and older adults in a single study. Examining in more detail the effects that arise as a consequence of normal ageing, further evidence suggests that surface-feature and location binding may differ in their attentional requirement (Brown & Brockmole, 2010; Elsley & Parmentier, 2009); with surface feature binding occurring without requiring the allocation of attentional resources beyond those needed to maintain individual features (Allen et al., 2006; Brown & Brockmole, 2010). Location binding, in contrast, may be an attentionally demanding process (Elsley & Parmentier, 2009). Accordingly, Experiment 2 examined this proposition directly by comparing surface-feature and location binding in younger adults under conditions of high and low attentional load. If older adult decline in feature binding performance is attentional in nature (and evidence does indeed suggest attentional decline in normal ageing: Sylvain-Roy, Lungu, & Belleville, 2014; Verhaeghen & Basak, 2005), in Experiment 2 we may observe effects analogous to that exhibited by older adults in Experiment 1 (in other words, younger adult performance under attentional load may mimic that of older adults).

The paradigm used in this chapter is based upon that developed by Allen et al. (2006) to assess binding and cognitive load; and later modified by Brown and Brockmole (2010) in order to assess binding and ageing. For the purposes of Chapter 1, however, the paradigm was amended to directly contrast surface-feature binding and location binding in a single study (as a function of age: Experiments 1 & 5; and as a function of attentional requirement: Experiments 2-4). The task requires participants to remember sets of colours, shapes, or locations individually; in addition to binary combinations of these features (i.e., colour-shape bindings; shape-location bindings and colour-location bindings). At the beginning of each block of trials, participants are instructed to remember a specific feature (colour, shape, location) or a combination of features. During the presentation phase, three stimuli are simultaneously displayed in distinct locations (i.e., the possible locations, of which there were six, were arranged in a circular fashion around a central fixation point). Following the array and a brief pattern mask, participants were presented with a probe item for which they were required to identify as either the same as one of the stimuli in the immediately preceding array or different. In single feature conditions (colour, shape, and location) a 'same' judgment is given to a probe feature that was present in the array and a 'different' judgment to a probe feature that was not in the array. In the combination conditions (colour-shape bindings, shape-location bindings, and colour-location bindings) a 'same' response should be given to a probe in which the combination of features matched one of those in the preceding array (e.g. that colour appeared in that location) while a 'different' response should be given to a probe that featured recombined features from the array (e.g. a colour that had appeared, but occupying a location that previously contained a different colour, for instance). The effect of binding is examined by comparing the single feature and combined feature conditions. In particular, in this task one is interested in whether performance in the combination conditions in particular (relative to the individual feature conditions) suffers as a consequence of either normal ageing or attentional load. An important methodological development for our adapted version of the paradigm is the inclusion of a structural pattern mask following presentation of the to-be-remembered array. The pattern mask was introduced to remove any residual iconic memory following presentation of the array. A structural mask rather than a standard visual noise mask was used to ensure the removal of the after-image for both visual and spatial information (Enns & Di Lollo, 2000).

Experiment 1 took a 2 (age group: younger, older) x6 (task type: colour , shape, location, colour & shape, shape & location, colour & location) mixed factorial design with age group as a between participants factor and task type was a within participants factor. It was carried out under concurrent articulation whereby participants were required to repeat out loud a number between 20 and 99 (selected at random) displayed at the beginning of each trial in order to safeguard against the verbal recoding of the visuo-spatial stimuli. Younger adults were expected to outperform older adults in all conditions and show the generally established finding (e.g. Allen et al., 2006) that memory performance for bound combinations of features is similar to memory performance for the more difficult of the constituent features (colours, shapes or locations). Additionally, based on past research, surface-feature binding should be relatively preserved in older adults (Brown & Brockmole, 2010), while a specific impairment in location binding performance may be observed in older adults relative to younger adults (Cowan et al., 2006). This would be demonstrated by comparatively poorer performance on the colour-location/shape-location combination conditions relative to the single feature conditions of their constituent features, an effect that should be absent for younger adults (*ageing-context hypothesis*).

2.2 Experiment 1: Feature Binding and Ageing

2.2.1 Method

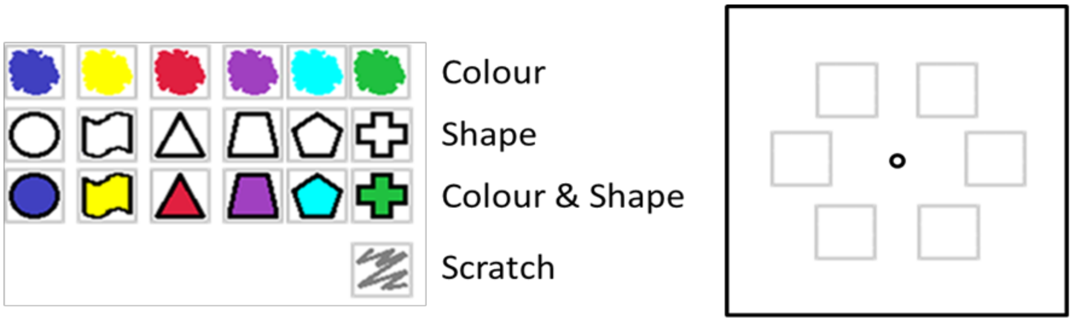
2.2.1.1 Participants

There were 33 participants in total. Twenty younger adults (18 females, 2 males), aged 18-29 years (M = 20.3, SD = 2.70), with a mean number of years of education of 12.65 (SD = 1.35) and a mean verbal IQ, predicted by the Weschler Test of Adult Reading (WTAR) of 113.3 (SD = 5.55). The older adult group consisted of 13 volunteers (8 females), aged 65-79 years (M = 71.77, SD = 4.87), with a mean number of years of education of 11.69 (SD = 2.25) and a mean verbal IQ, predicted by the WTAR of 116.0 (SD = 6.03). Predicted verbal IQ did not significantly differ between younger and older adults (t (31) = 1.32, p = .10). Older adults were screened for atypical cognitive decline using the Montreal

Cognitive Assessment (MoCA; Nasrendine et al., 2005). In accordance with Luis, Keegan and Mullen (2009) a cut-off score of 23 was used (with scores lower than 23 being considered markers of mild cognitive impairment). The mean score on the MoCA across older adults was 27.54 (*SD* = 1.81) with no participants meeting the exclusion criteria. In addition, participants reported no significant memory problems and normal or corrected-to-normal vision. All participants received either course credit or a small honorarium for participation and were naïve to the experimental aims.

2.2.1.2 Materials

The three constituent elements of stimuli were colour, shape, and location. Consistent with Allen et al., (2006) colours consisted of red (R-255, G-0, B-0), yellow (R-255, G-255, B-0), blue (R-64, G-64, B-192), green (R-32, G-192, B-64), cyan (R-0, G-255, B-255), and purple (R-160, G-64, B-192). The shapes consistent of circle, triangle, pentagon, wave, trapezoid, and cross. The six possible locations are shown in Figure 2.1. In the colours-only condition, colours were presented in a non-canonically shaped 'blob' (neutral shape). In the shapes-only condition, shapes were drawn in a black outline and filled white to match the background (neutral colour). The location-only condition used a single stimulus of a grey scratch mark (neutral shape and colour: Figure 2.1). Colour-shape conjunctions combined one of the six shapes filled with one of the six colours sampled without replacement within each trial. The same was done for colour-location and shape-location conjunctions, whereby each surface-feature (colour or shape) was combined with each of the six locations, and sampled without replacement in each trial. Each stimulus was presented within a 1° x 1° black frame to reduce variations in spatial configuration caused by the shapes (Delvenne, Braithwaite, Riddoch & Humphreys, 2002). This task was purpose written using OpenSesame (Mathôt, Schreij & Theeuwes, 2012) with the Expyriment Library (Krause & Lindemann, 2014) and presented on a 20" monitor. Viewing distance was not constrained but was approximately 57cm. All responses were collected via a standard keyboard.



Example Stimuli. Colours and shapes based on Allen et al. (2006) with the addition of a Scratch stimulus to mark locations in the location only condition

TBR array Stimulus locations: Centre point of each location is 2 degrees of visual angle from fixation point

Figure 2.1 Example stimuli and map of stimulus locations. Colours were displayed in a non-canonical blob and shapes with a 3 point black outline.

2.2.1.3 Design

A 2 (age group: younger, older) x6 (task type: colour , shape, location, colour & shape, shape & location, colour & location) mixed factorial design was employed where age group was a between participants factor while task type was a within participants factor. Recognition performance was assessed using d'. In addition to an omnibus analysis of the data, smaller (more targeted) analyses comparing each combination condition with its constituent features (colour, shape, colour & shape; colour, location, colour & location; shape, location, shape & location) were conducted to assess our specific predictions regarding binding performance across younger and older age groups. A bayesian ANOVA was also conducted to complement each traditional ANOVA with all models considered equally likely due to paradigm adaptations (introduction of location task types) and the introduction of older adult participants which makes the impact of the Age Group variable on the models impossible to predict. T-tests were also supplemented with their bayesian equivalents. All analyses were again conducted using JASP statistical software (JASP Team, 2016).

2.2.1.4 Procedure

Both younger and older adults completed the Weschler Test of Adult Reading (WTAR) to gain an estimate of Verbal IQ. This assessment consists of 50 words, each with an opaque pronunciation such that one needs prior experience with the word in order to correctly pronounce it. The raw scores were cross referenced with age-based scoring tables to produce an approximate verbal IQ. Older Adults also completed the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) as a measure of cognitive functioning. This is a short form cognitive assessment developed to assist in the detection of Mild Cognitive Impairment (though used here simply to confirm older participants as ageing healthily) and consists of thirty questions scoring participants on different facets of memory performance.

Once all pre-tests had been completed, participants undertook the experimental task. Experiment 1 compared younger and older adult memory accuracy for feature-shape and location bindings. For all age comparisons in this chapter, Experiment 1 was carried out under conditions of concurrent articulation (this term is preferred to articulatory suppression since Jalbert, Neath & Suprenant, 2011, notes that it is agnostic to the effects of the manipulation on cognitive processing) whereby participants were required to repeat out loud a number between 20 and 99. Concurrent articulation was included in order to disrupt verbal recoding of the visuo-spatial stimuli. In that task, each trial began with the presentation of a random two digit number (between 20 and 99) for 1000ms. Participants were instructed to repeat out loud that number at a rate of two words per second for the duration of the trial (to be carried out from the moment the number was displayed on screen, until the participant pressed a response key on the keyboard) and compliance with this instruction was monitored by the experimenter throughout the study.

A central fixation point followed this for 500ms, after which the to-be-remembered (TBR) array consisting of three objects from the task relevant feature set (described in detail below) was presented for 250ms and followed by a 100ms pattern mask. After a further delay of 800ms the probe was presented and participants indicated whether 'yes' the item was present in the array or 'no' the item was not present in the array by pressing the 'z' or 'm' keys on a keyboard (with the key mappings reversed for half of the participants). The precise nature of this decision varied with task instructions for each block of trials, discussed below. The inter-trial-interval was 1000ms. Each stimulus, or stimulus combination, appeared equally often within each condition across the experiment. The experiment was divided into six blocks (Colour; Shape; Location; Colour & Shape; Colour & Location; Shape & Location), each of which consisted of 10 practice trials followed by a block of 50 experimental trials (with a self-paced break after 25 trials). Within each task type, half of the trials were target present, while the other half were lures (randomised across the task). The order of conditions was counterbalanced using a Latin-square resulting in 9 different orders of administration.

Memory arrays consisted of three stimuli (the nature of which varied depending on the condition undertaken – see Figure 2.2 for an illustration of what was shown for each feature/combination condition) each presented in one of six locations, sampled without replacement. Locations were distributed in a circular fashion around a central fixation point with the centre of each stimulus approximately two degrees of visual angle from the central fixation, assuming a viewing distance of approximately 57cm. Probe arrays consisted of a single stimulus, the presentation of which differed across the six task conditions in that in each condition the probe array consisted only of features relevant to the task (with the exception of the unavoidable use of locations). For example, in the colour task all stimuli were colours presented in a non-canonical blob while in the shapes task, all stimuli were black outline shapes with no colour fill. See Figure 2.2 for a detailed explanation.

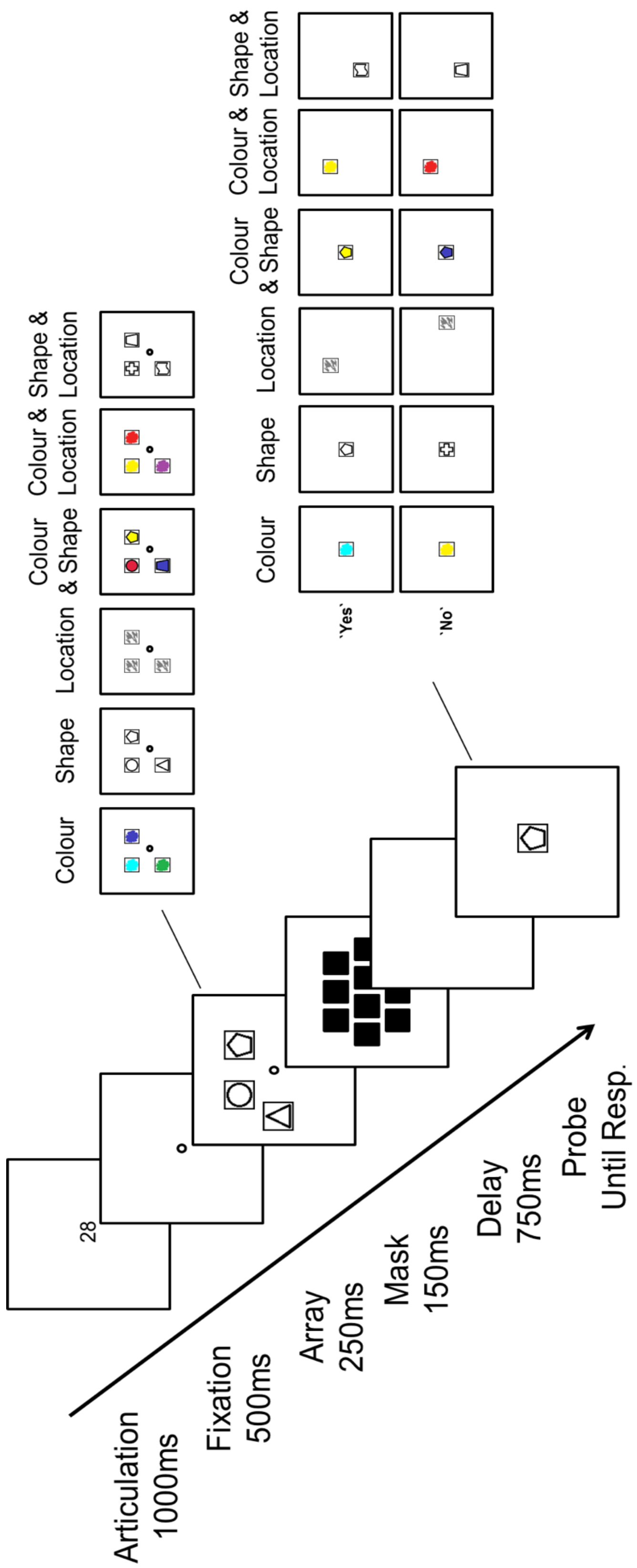


Figure 2.2. Trial procedure and example arrays and probes in each condition of Experiment 1.

Single Feature conditions: In the colours task, the array consisted of three different coloured non-canonically shaped blobs (i.e., neutral shape) displayed simultaneously, each in one of the six stimulus locations. The probe was a coloured non-canonically shaped blob presented in a central (neutral) location in one of the six colours described above. In the shapes task, the array consisted of three of the six possible unfilled black outline shapes presented simultaneously in different locations while the probe consisted of a single, centrally presented (neutral location) outline shape. In the location-only condition the array consisted of three 'scratches' (neutral colour and shape) displayed simultaneously in three of the six possible locations (all stimuli here were visually identical) and the probe was the 'scratch' presented in one of the six locations. A "yes" response was given for a probe stimulus that was present in the preceding array, and a "no" response given for a probe not present in the preceding array (1:1 ratio).

Feature Binding conditions: The array in the colour-shape binding condition consisted of three coloured shapes simultaneously presented in three of the six possible locations. The probe consisted of a single coloured shape presented in a central (neutral) location. On match trials, the colour-shape combination of the probe matched a colour-shape combination in the array; while on non-match trials, a colour and shape from the array were recombined to create a lure. In the colour- location binding condition the array consisted of three coloured noncanonically shaped blobs appearing in three of the six locations. The probe was a non-canonically shaped coloured blob presented in one of the locations occupied in the TBR array. On match trials, the colour-location combination of the probe matched the array, while on non-match trials, a colour and shape feature were recombined to form the probe. In the shape-location binding condition the array consisted of three of the unfilled shapes appearing in three of the locations. The probe consisted of a shape presented in one of the locations occupied in the TBR array. On match trials, the probe consisted of a shape-location combination that was present in the TBR array, while on lure trials, a shape switched locations with a different TBR shape. See Figure 2.2 for a diagrammatic explanation of the “yes” (match) and “no” (lure) response trial types for each condition. The task lasted approximately 50 minutes.

2.2.1.5 Data Analysis

The analyses presented below are initially presented as a multifactorial 2 (age group: young adult; older adult) X 6 (task type: Colour, Shape, Location, Colour & Shape, Colour & Location, Shape & Location) mixed ANOVA. Following this, in order to ensure that each facet of this study can be directly compared to Allen et al. (2006) and Brown and Brockmole (2010), each analysis is divided so that each binding type (and constituent features) is assessed independently as a function of age. For each binding type, the data were subjected to 2 (age group: younger adult; older adult) x 3 (task type: feature, feature, feature conjunction) ANOVA for repeated measures, with age group as a between subjects factor. As accuracy was stressed rather than speed, the analyses presented here focus on accuracy (d’)[1]. As in Allen et al. (2006), response latencies are not reported.

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[1] D-prime cannot be calculated from scores of 0 or 1. Thus, in accordance with Stanislaw and Todorov, (1999), these hit and false alarm rates were adjusted using the $1–1/2N$ and $1/2N$ formulas respectively where N is equal to the total number of “no” (N=25) or “yes” (N=25) trials.

2.2.2 Results

Omnibus Analysis: A 2 (age group: younger, older) x 6 (task type: colour, shape, location, colour & shape, colour & location, shape & location) mixed ANOVA revealed a significant main effect of task type, F (5,150) = 14.53, MSE = 4.97, p < .001, ηp^2 = .33, BF_{10} = 2.71^{e+11}); see Table 2.1 for descriptive statistics, and post-hoc comparisons; comparisons will be described in depth for each of the more targeted analyses. There was a significant main effect of age group, F (1,30) = 17.47, MSE = 24.60, p < .001, ηp^2 = .37, BF_{10} = 85.81, with younger adults (M = 2.38, SD =0.79) outperforming older adults (M = 1.64, SD = 0.83); and no significant interaction between factors, F (5,150) = 0.96, MSE = 0.33, p = .44, ηp^2 = .03, BF_{10} = 0.16.

Table 2.1. Descriptive statistics and post-hoc comparisons exploring the main effect of task type in Experiment 1.

			Comparisons (df=31) t-statistic (BF_{10})					
Task Type	Mean	Standard Deviation	Colour	Shape	Location	Colour & Shape	Colour & Location	Shape & Location
Colour	2.55	0.79	-	7.26** (394242.91)	0.10 (0.19)	6.17** (22592.19)	1.88 (0.90)	4.34** (187.61)
Shape	1.78	0.64	-	-	5.71** (6655.17)	1.88 (0.90)	3.34** (16.22)	1.41 (0.46)
Location	2.53	0.88	-	-	-	6.45** (47362.62)	1.65 (0.63)	4.34** (186.81)
Colour & Shape	1.51	0.79	-	-	-	-	4.35** (190.42)	3.10** (9.50)
Colour & Location	2.29	0.95	-	-	-	-	-	1.92 (0.96)
Shape & Location	1.96	0.74	-	-	-	-	-	-

*p < .05
**p < .01

Surface-Feature Binding: Accuracy scores (d') were subjected to a 2 (age group: younger, older) x 3 (task type: shape, location, combination) mixed ANOVA. The analysis indicated a main effect of task type, F (2,60) = 24.99, MSE = 8.15, p < .001 ηp^2 = .45, BF_{10} = 1.31^{e+8}, whereby performance in the colour condition (M = 2.55, SD = 0.79) was superior to that in the shape condition (M = 1.78, SD = 0.64; t (31) = 7.26, p < .001, d = 1.07, BF_{10} = 3.94^{e+5}); and the colour-shape combination condition (M = 1.51, SD = 0.79; t (31) = 6.18, p < .001, d = 1.32, BF_{10} = 2.26^{e+4}), and the shape condition elicited better performance than the colour-shape combination condition (t (31) = 1.88, p = .03, d = 0.38, BF_{10} = 0.90) though the Bayes Factor was insensitive indicating that a difference is just 1.11 times more likely than the null. Furthermore, there was a significant main effect of age group, F (1,30) = 17.173, MSE = 11.36, p < .001, ηp^2 = .94, BF_{10} = 32.09) with older adults performing worse than younger adults over all (older: M = 1.50; SD = 0.74; younger: M = 2.21, SD = 0.81); and no interaction between factors, F (2,58) = 0.570, MSE = 0.19, p = .568, ηp^2 = .02, BF_{10} = 0.27). The data are illustrated in Figure 2.3.

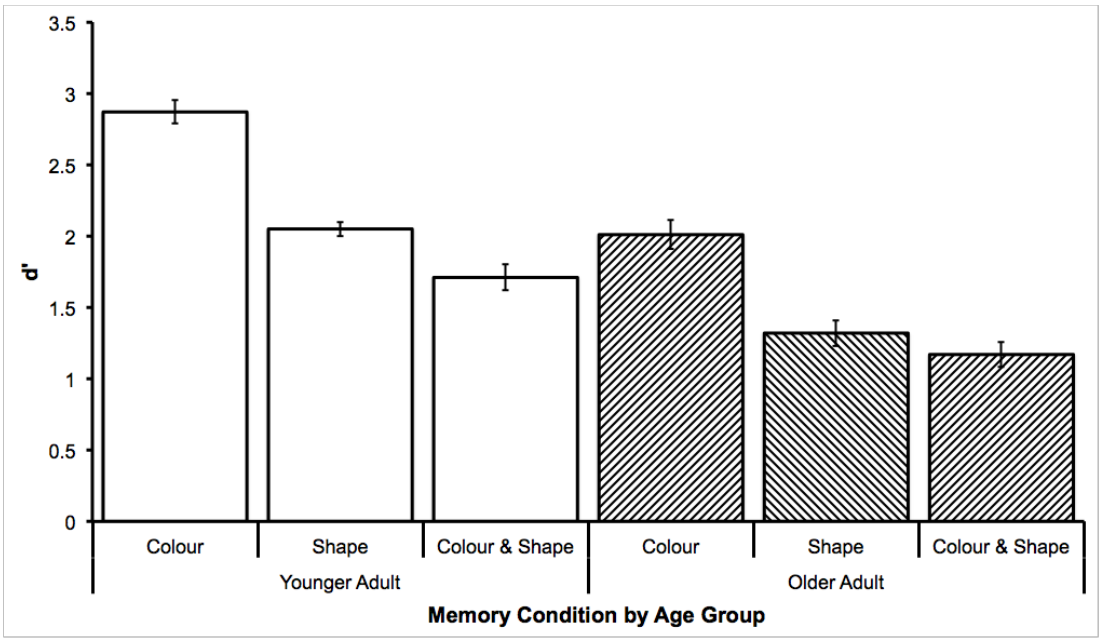


Figure 2.3. Plot showing d' scores for the colour and shape combination condition and its constituent features for each age group in Experiment 1. Error bars represent standard error of the mean.

In sum, these data suggest that surface-feature binding remains intact irrespective of ageing, with older adults showing a general decline in performance.

Colour-Location Binding: Accuracy scores (d') were subjected to a similar 2 (age group: younger adults, older adults) x 3 (task type: shape, location, combination) mixed ANOVA. The analysis indicated no main effect of task type F (2, 60) = 2.45, MSE = 0.79, p = .10, ηp^2 = .08, BF_{10} = 0.51) with the Bayes factor insensitive and suggesting the null to be only 1.96 times more likely than the alternative. There was a significant main effect of age group, F (1,30) = 16.15, MSE = 18.16. p < .001, ηp^2 = .34, BF_{10} = 74.15, with older adult accuracy worse overall (older: M = 1.90; SD = 0.63; younger: M = 2.79, SD = 0.61); but no interaction between task type and age, F (2,60) = 0.42, MSE = 0.14, p = .66, ηp^2 = .01, BF_{10} = 0.20. The data are presented in Figure 2.4.

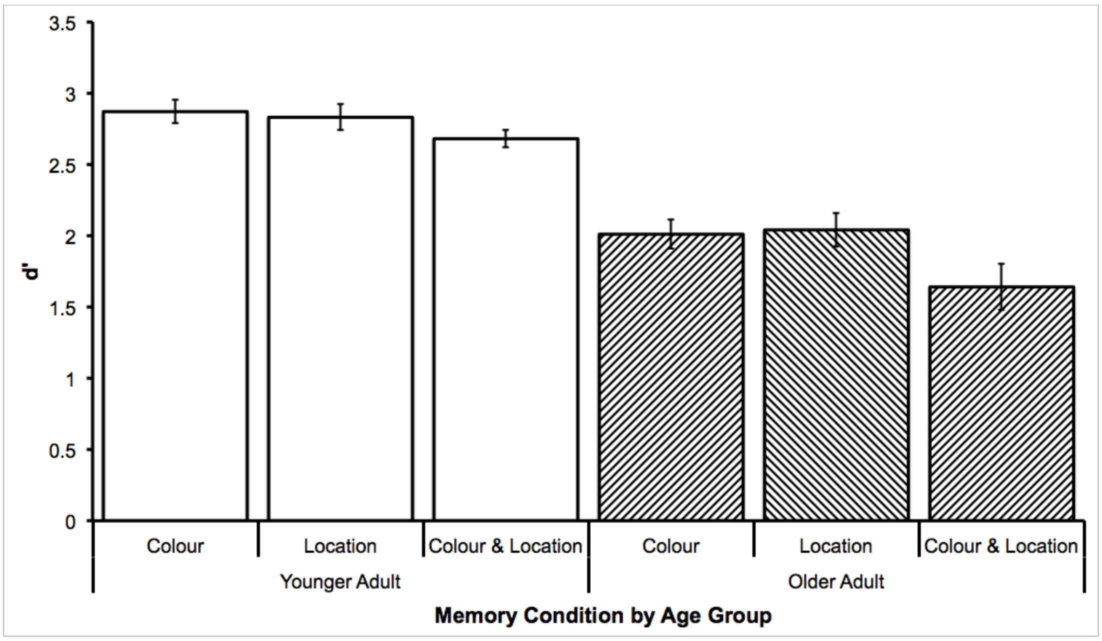


Figure 2.4. Plot showing d' scores for the colour and location combination condition and its constituent features for each age group in Experiment 1. Error bars represent standard error of the mean.

The colour-location focused ANOVA shows again a general decline in performance as a function of age, with both the age groups showing a similar pattern of performance.

Shape-Location Binding: A 2 (age group: younger adults, older adults) x 3 (task type: shape, location, combination) mixed ANOVA conducted on d' values revealed a significant main effect of task type, F (2,60) = 15.95, MSE = 4.45, p < .001, ηp^2 = .35, BF_{10} = 2.23^{e+4}. Performance was better in the location condition (M = 2.53, SD = 0.88) relative to the shape condition (M = 1.78, SD = 0.64; t (31) = 5.71, p < .001, d = 0.97, BF_{10} = 6655.17). Location also differed from the shape-location condition (M = 1.96, SD = 0.74; t (31) = 4.34 $p < .001$, d = 0.70, BF_{10} = 186.81). The shape condition did not differ significantly from the shape-location condition (t(31) = 1.41, p = .08, d = 0.26, BF_{10} = 0.46) though this difference was not significant and the Bayes Factor tended toward support for the null, suggesting no difference. In addition, there was a significant main effect of age group, F (1,30) = 11.22, MSE = 9.97, p = .002, ηp^2 = .27, BF_{10} =14.66; with older adults less accurate than younger adults (older: M = 1.68; SD = 0.57; younger: M = 2.34, SD = 0.55); while again, the interaction between feature type and age group was non-significant, F (2,60) = 0.77, MSE = 0.22, p = .47, ηp^2 = .02, BF_{10} = 0.31. The data are illustrated below in Figure 2.5.

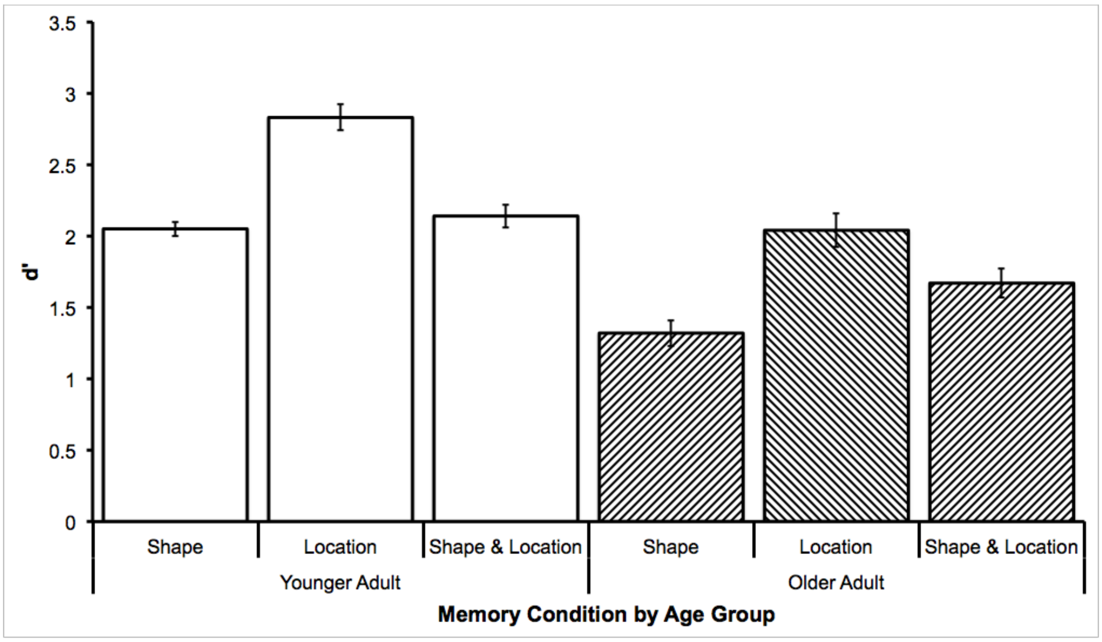


Figure 2.5. Plot showing d' scores for the shape and location combination condition and its constituent features for each age group in Experiment 1. Error bars represent standard error of the mean.

In summary, the results from Experiment 1 indicate no specific age related binding deficit in either surface-feature binding or location binding ability. Although older adult performance was worse overall, any difference was uniform across all memory conditions.

2.2.3 Discussion

Experiment 1 directly tested the *ageing-context hypothesis* which was based on the idea that older adults would exhibit a disproportionate impairment in the colour-location and shape-location conditions relative to younger adults, while their shape-colour binding should be relatively preserved. The results of Experiment 1 suggest that despite overall reductions in accuracy for older adults relative to younger adults, there was no specific impairment in performance on any of the binding conditions. This finding stands in contrast to literature suggesting that location binding may be impaired in older adults (Cowan et al., 2006). In short, the pattern of performance from older adults is qualitatively equivalent to younger adults but quantitatively reduced. Differences between individual task types are best discussed in light of the ANOVAs conducted on individual feature binding tasks (colour & shape, colour & location, shape & location) and their constituent features.

Separate analysis of the feature combination tasks (conducted to provide a more direct comparison to Brown and Brockmole, 2010), yielded two key findings. First, the data replicate previous studies suggesting that surface-feature binding is relatively preserved in older adults (Brown & Brockmole, 2010). While older adults exhibited overall impaired memory performance compared to younger adults when binding colour and shape features, the absence of an interaction indicated no specific impairment with surface-feature binding beyond the general age-related memory impairment. Task type comparisons revealed patterns of performance consistent with past research (Allen et al., 2006; Brown & Brockmole, 2010); namely, that memory for colours was significantly better than both shapes and colour-shape combinations. Second, separate analyses on location binding (shape-location and colour-location) suggest that older adults are not disproportionately impaired on location binding tasks relative to individual feature tasks. The pattern of performance for older adults again qualitatively matched that of the younger adults. In the colour-location condition, the absence of a main effect of task type could suggest that object to location binding may be no more cognitively demanding than memory for single features, a proposition that is assessed more directly in Experiment 2. In contrast, there was a significant main effect of task type for the shape-location binding condition. This effect appears to be driven by high levels of accuracy for location memory relative to shape memory. This is analogous to the surface-feature condition where accuracy for colour exceeded that for shape. Since colour and location exhibited high levels of accuracy (relative to shapes), it is therefore unsurprising that location and colour did not differ in the colour-location condition.

In summary, Experiment 1 suggests that the *ageing-context* hypothesis (which predicts age-related impairments whenever the binding of contextual features, in this instance location, is required) is not supported suggesting that both surface-feature binding and location binding remain relatively preserved in older age. However, an alternative explanation for the findings from Experiment 1 is that older adults only exhibit binding deficits when the process of binding is cognitively effortful (an account previously outlined as the *ageing-attention* hypothesis). If neither surface-feature binding nor location binding is effortful, then this may explain the absence of age-related binding deficits in Experiment 1. To address this issue, Experiment 2 replicated the procedures of Experiment 1, with the exception of the addition of a cognitive load condition. Only younger adult performance was assessed. If binding for both surface-feature and location binding is unaffected by cognitive load, it suggests that neither type of binding is cognitively demanding. The findings of Experiment 1 would, therefore, remain somewhat consistent with the *ageing-attention* hypothesis (but not the ageing-context hypothesis).

2.3 Experiment 2: Surface-feature binding, location binding, and the role of attentional resources

Running parallel to the investigation of age related changes in feature binding, Experiment 2 investigated the contribution of general attentional resources to surface-feature binding and location binding. The rationale for Experiment 2 was two-fold. First, there currently exists some disagreement in the literature as to whether surface-feature binding is an attentionally demanding or automatic process (with most studies supporting the latter contention). For instance, Allen et al. (2006) and Allen et al. (2012) both find evidence to suggest that surface feature binding is no more resource demanding than memory for single features. In contrast, Brown and Brockmole (2010) showed that higher attentional load impacted memory performance for bound combinations of surface features to a greater extent than memory performance for single features. Furthermore, Elsley and Parmentier (2009) reported evidence suggesting that location binding (between verbal and spatial features) can be resource demanding, but did so using a substantially different experimental paradigm to that used by Allen et al. (2006) and Brown and Brockmole (2010). Thus, the first aim of Experiment 2 was to directly investigate the attentional demand of both surface-feature and location binding within a single paradigm.

The second (related) aim of Experiment 2 was to assess whether older adults in Experiment 1 did not show evidence of binding deficits because both binding types assessed in that experiment required no additional cognitive effort (beyond that needed for individual features). Indeed, the *ageing-attention* hypothesis suggests that older adults should be impaired under circumstances where the binding task under investigation requires cognitive effort. Experiment 2 indirectly tests this proposition by exploring whether a secondary demanding task disrupts surface-feature and/or location binding in a younger adult sample. If disruption is reported, the proposition that older adults only show impairments on effortful binding tasks would be contradicted. Conversely, if no disruptive effect of cognitive load across the three binding types is found in Experiment 2, then the results of Experiment 1 are entirely consistent with the *ageing-attention* hypothesis.

2.3.1 Method

2.3.1.1 Participants

Nineteen younger adults from the student population of Bournemouth University and the local area (16 females, 3 males,), aged 18-29 years (M = 20.03, SD = 1.89) completed this study, which took approximately 60 minutes per participant. All participants received either course credit or an honorarium for participation and reported normal or corrected-to-normal vision.

2.3.1.2 Materials

The materials used in Experiment 2 were identical to those described for Experiment 1.

2.3.1.3 Design

Experiment 2 used a 2 (load vs no load) x 6 (memory condition) within-participants design, and contrasted recognition performance (d') across the six memory conditions used in Experiment 1 (colour, shape, location, colour & shape, colour & location, shape & location) under low and high cognitive load (achieved by concurrent articulation and counting backwards in threes respectively).

2.3.1.4 Procedure

The experimental procedure followed that described for Experiment 1 with the following exceptions. Due to the testing of younger adults only, the WTAR was not administered. As before, the task consisted of six memory conditions with participants instructed to remember one of the following in each block: Colours only; Shapes only; Locations only; Colours and Shapes; Colours and locations; Shapes and Locations, with trial timings identical to those used in Experiment 1. Each participant now completed the 6 blocks twice, once with concurrent articulation instructions (low cognitive load) whereby they were instructed to repeat out loud the number presented at the start of each trial; and once with instructions to count backwards in threes out loud from the presented number (high cognitive load). Participants were required to maintain the concurrent task throughout encoding, maintenance, and retrieval in each trial, only finishing articulation when a response key had been pressed. Compliance was monitored by the experimenter. Cognitive load order was blocked and counter-balanced across participants. Each block consisted of 6 practice trials followed by 30 critical trials.

2.3.1.5 Data Analysis

As described for Experiment 1, accuracy performance (d') was calculated for each binding condition and analysed with an overall 6 (task type) x 2 (cognitive load) repeated measures ANOVA. Then, enabling comparison to previous research (Allen et al., 2006), two separate 3 (task type) x 2 (cognitive load) repeated measures ANOVAs were conducted for each feature binding condition (surface feature binding and location binding) and its constituent features. In respect of how d' was calculated, the change in the number of experimental trials meant that the adjusted scores of 1 or 0 were different to those for Experiment 1, but again calculated in accordance with Stanislaw and Todorov, (1999) as follows: hit and false alarm rates were adjusted using the 1-1/2*N* and

$1/2N$ formulas respectively where N is equal to the total number of "no" (N=15) or "yes" (N=15) trials.

2.3.2 Results

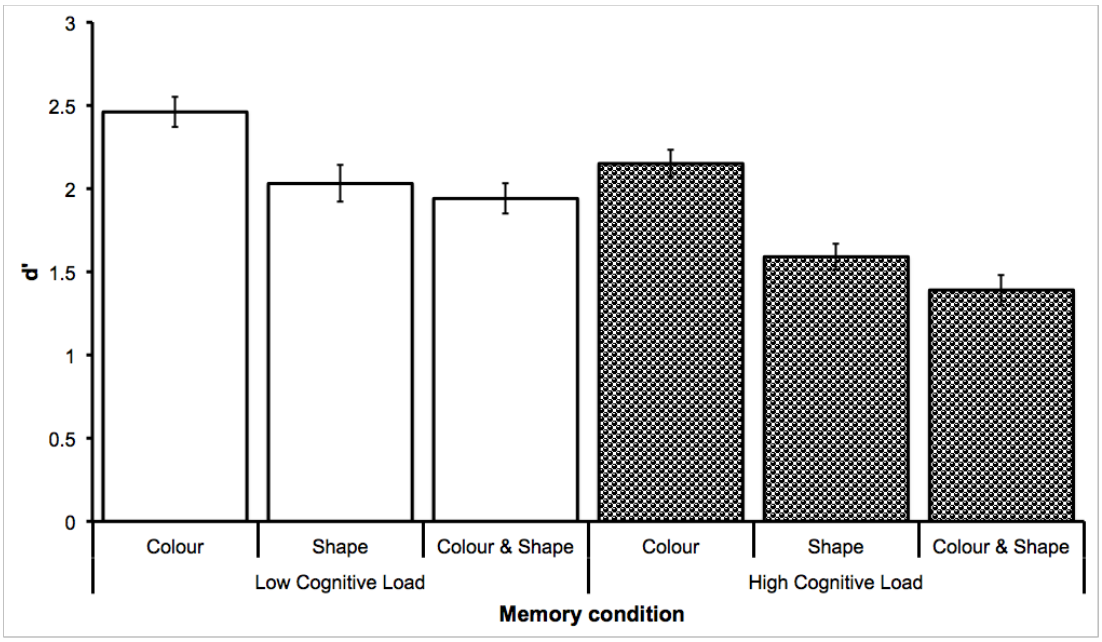
Omnibus Analysis: A 6 (task type: colour, shape, location, colour & shape, colour & location, shape & location) x 2 (load: low, high) repeated measures ANOVA revealed a significant main effect of task type, F (5,155) = 13.63, MSE = 4.69, p < .001, ηp^2 = .30, BF_{10} = 2.09^{e+8}); see table 2.2 for descriptive statistics, and post-hoc comparisons (again, comparisons will be described in depth for each of the more targeted analyses.). There was a significant detrimental effect of load, F (1,31) = 19.02, MSE = 4.69, p < .001, ηp^2 = .38, BF_{10} = 7925.57 (low load: M = 2.38, SD = 0.79; high load M = 1.51, SD = 0.93); and no significant interaction between factors, F (5,155) = 1.26, MSE = 0.43, p = .29, ηp^2 = .04, BF_{10} = 0.17.

Table 2.2. Descriptive statistics, and post-hoc comparisons exploring the main effect of task type in Experiment 2.

			Comparisons (df=18) t-statistic (BF_{10})					
Task Type	Mean	Standard Deviation	Colour	Shape	Location	Colour & Shape	Colour & Location	Shape & Location
Colour	2.31	0.65	-	4.79** (197.59)	7.04** (12891.65)	5.69** (1109.65)	1.42 (0.57)	3.23** (9.91)
Shape	1.81	0.67	-	-	4.74** (182.84)	1.10 (0.40)	2.68* (3.65)	0.30 (0.25)
Location	1.23	0.42	-	-	-	2.39* (2.23)	5.21** (443.12)	3.89** (34.91)
Colour & Shape	1.67	0.72	-	-	-	-	4.16** (59.17)	1.50 (0.62)
Colour & Location	2.14	0.76	-	-	-	-	-	2.28* (1.86)
Shape & Location	1.85	0.77	-	-	-	-	-	-

*p < .05
**p < .01

Colour-Shape Binding: A 3 (task type: colour, shape, combination) x 2 (load: low, high) repeated measures ANOVA indicated a significant main effect of task type, F (2,36) = 16.58, MSE = 4.24, p< .001, ηp^2 = .48, BF_{10} = 1137.95); whereby colour (M=2.31, SD=0.65) produced better performance than shape (M=1.81, SD=0.67; t(19)=4.79, p <.001, d = 0.76, BF_{10} = 192.01), colour elicited higher performance than colour-shape combination (M=1.67, SD=0.71; t(18)=5.71, p <.001, d = 0.94, BF_{10} = 1115.21) and shape performance was no different to colour-shape combination condition performance (t(18)=1.10, p =.14, d = 0.20, BF_{10} = 0.40). There was a significant main effect of load, F (1,18) = 8.10, MSE = 5.37, p = .01, ηp^2 = .31, BF_{10} = 90.63) with low load (M = 2.15, SD = 0.85) yielding better performance than high load (M = 1.71, SD = 0.79) and, as predicted, no significant interaction between factors, F (2,36) = 0.94, MSE = 0.14, p = 0.40, ηp^2 = .05, BF_{10} = 0.20). The data are presented in Figure 2.6.



*F*igure 2.6. Plot showing d' scores for the colour and shape combination condition and its constituent features for each cognitive load condition in Experiment 2. Error bars represent standard error of the mean.

Colour-Location Binding: A 3 (task type: colour, location, commination) x 2 (load: low, high) repeated measures ANOVA revealed a significant main effect of task type, F (2,36) = 29.56, MSE = 12.64, p < .01, ηp^2 = .62, BF_{10} = 2.46^{e+14}; whereby colour (M = 2.31, SD = 0.65) produced better performance than location (M = 1.23, SD = 0.42; t(18)=7.04, p <.001, d = 1.97, BF_{10} =12836.03), location condition performance was poorer than colour-location combination performance (M = 2.14, SD = 0.76; t(18)=5.20, p <.001, d = 1.48, BF_{10} = 444.90) and colour performance was marginally, though not significantly, different to colour-shape combination (t(18)=1.43, p =.08, d = 0.24, BF_{10} = 0.57) with the

Bayes Factor here indicating that the null is 1.75 times more likely than the alternative; a significant main effect of load, *F* (1,18) = 6.49, MSE = 2.36, *p* = .02, ηp^2 = .27, BF_{10} = 1.56, with low load (M = 2.04, SD = 0.90) again yielding better performance than high load (M = 1.75, SD = 0.79), although the Bayes Factor are insensitive to the difference here with the alternative just 1.56 times more likely than the null. There was no significant interaction between factors, *F* (2,36) = 1.25, MSE = 0.18, *p* = .298, ηp^2 = .07, BF_{10} = 0.21. The data are presented in Figure 2.7.

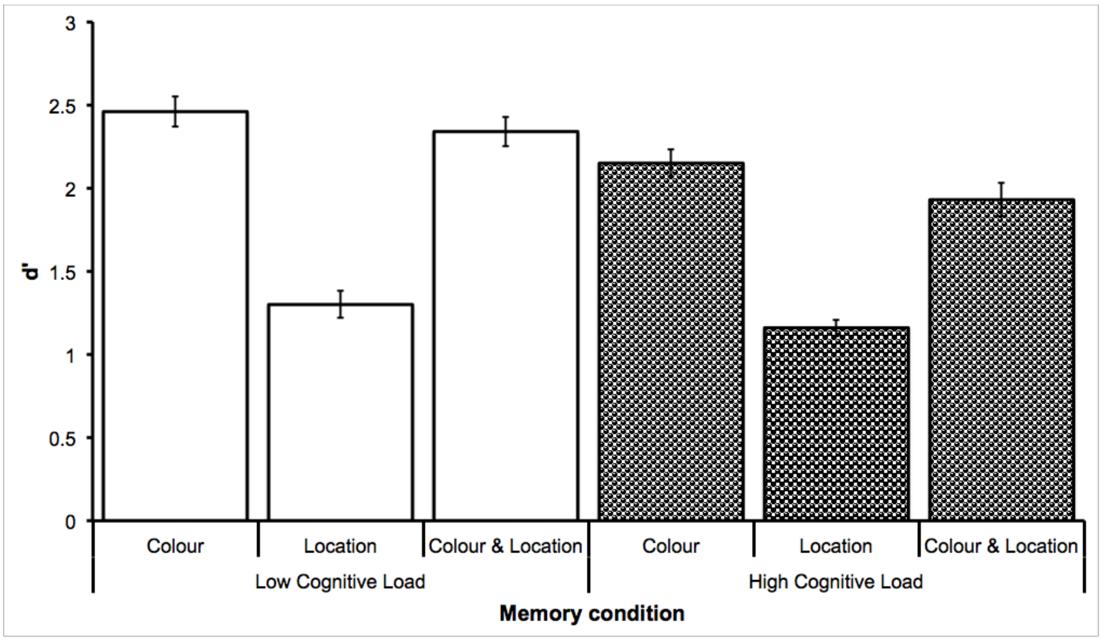


Figure 2.7. Plot showing d' scores for the colour and location combination condition and its constituent features for each cognitive load condition in Experiment 2. Error bars represent standard error of the mean.

Shape-Location Binding: A 3 (task type: shape, location, combination) x 2 (load: low, high) repeated measures ANOVA revealed a significant main effect of task type, *F* (2,36) = 12.91, *MSE* = 4.53, *p* < .001, ηp^2 = .42, BF_{10} = 361.94); whereby shape (*M* = 1.81, *SD* = 0.67) produced more accurate performance than location

(M=1.23, SD=0.42; t (18)=4.75, p <.001, d = 1.04, BF_{10} = 189.01), location elicited poorer performance than shape-location combination (M = 1.85, SD = 0.77; t (18)=3.88, p <.001, d = 1.00, BF_{10} = 34.59), and shape performance was no different to shape-location condition performance (t (18)=0.28, p =.39, d = 0.06, BF_{10} = 0.25); a significant main effect of load, F (1,18) = 14.28, MSE = 5.51, p = .001, ηp^2 = .44, BF_{10} = 36.22, with low load (M = 1.85, SD = 0.85) again yielding better performance than high load (M = 1.41, SD = 0.78) and again no significant interaction between factors, F (2,36) = 2.35, MSE = .86, p = .11, ηp^2 = .12, BF_{10} = 0.79, although here the Bayes Factors indicate the null to be just 1.27 times more likely than the alternative revealing the data to be insensitive in this case. The data are presented in Figure 2.8.

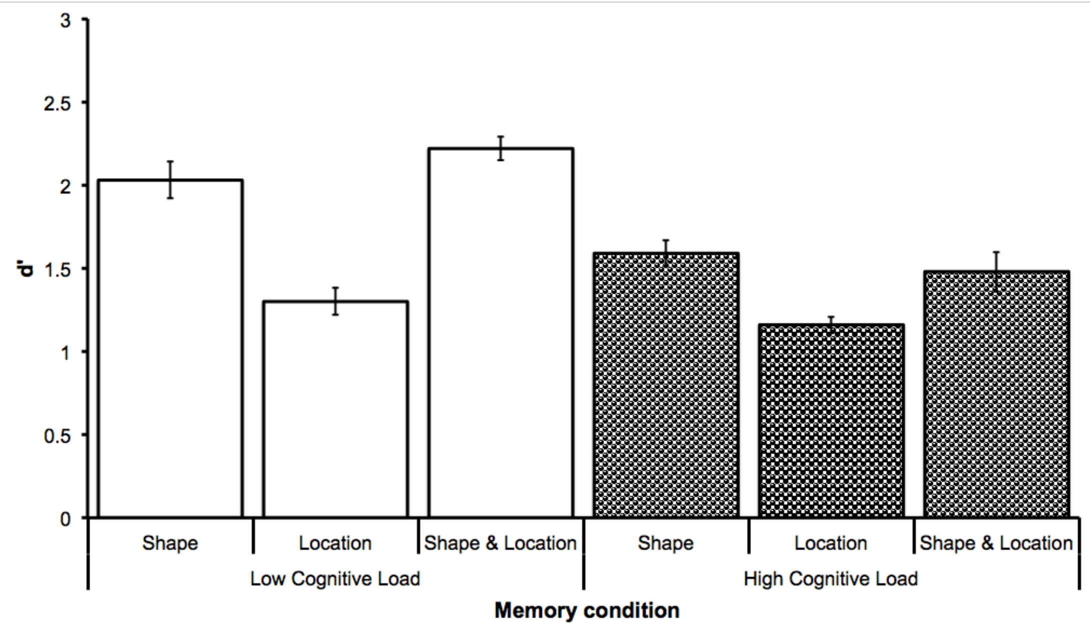


Figure 2.8. Plot showing d' scores for the shape and location combination condition and its constituent features for each cognitive load condition in Experiment 2. Error bars represent standard error of the mean.

The results from Experiment 2 show no indication that either surface feature binding nor location binding draw more heavily on attentional resources than memory for single features, any difference was uniform across all memory conditions.

2.3 Discussion

Experiment 2 examined whether surface-feature binding and location binding require attentional resources. The experiment was motivated by previous contrasting findings that demonstrate surface-feature binding seemingly draws no more on attentional resources than single feature memory (Allen et al., 2006; 2012), while location binding may be a process that is more demanding of attentional resources than single feature memory (Elsley and Parmentier, 2009). The first aim of Experiment 2 was therefore to directly investigate the attentional demand of both surface-feature and location binding within a single paradigm. The second motivating factor of Experiment 2 was to assess whether older adults in Experiment 1 did not show evidence of binding deficits because both binding types assessed in that experiment required no additional cognitive effort (beyond that needed for individual features).

This question speaks directly to the findings of Experiment 1 where no binding-specific deficits in older adults were found. According to the *ageing-attention hypothesis,* any deficit in surface-feature binding or location binding may be attributed to an age-related decline in general attentional resources. Therefore, if both types of binding are effortless, one would not predict any binding deficits in older adults in Experiment 1. In contrast to that prediction, Experiment 2 revealed no interaction between task type and cognitive load. This, combined with a consistent main effect of load indicates that single feature memory and both classes of feature binding draw on attentional resources to a similar extent. In respect to the binding class specific analyses, the results of Experiment 2 yielded two critical findings. First, the surface-feature condition produced results compatible with previous studies (Allen et al., 2006; Allen et al., 2012) suggesting that surface-feature binding is immune to manipulations of cognitive load insofar as it does not draw on attentional resources beyond those ascribed to the maintenance of individual features (Allen et al., 2006; Allen et al., 2012)., Additionally, performance in the more difficult of the single feature conditions, in this case shape, showed no difference to that in the colour-shape binding condition, a finding common to previous research (Allen et al., 2006; Allen et al., 2012).

Second, load by task type interactions were non-significant in the colour-location and shape-location binding conditions, suggesting that location binding is also immune to manipulations of cognitive load. As noted above, typically the more difficult of the constituent features is found to be no more difficult than the bound combination condition in question. This was not found for location binding in both the colour-location, and shape-location comparisons, the most difficult task proved to be location only. Such a finding is not predicted by the existing literature. Indeed, it is counterintuitive on the basis that, typically, VSTM can maintain around 4 simple visual features (e.g., Luck & Vogel, 1997) but approximately 6 spatial locations (e.g., Simons, 1996). Consequently, it follows that memory for locations should be superior to memory for shapes or colours as assessed in our individual feature tasks (as indeed it was in Experiment 1).

Lower performance for the location single feature condition (compared to the colour-location and shape-location binding conditions) was at first a perplexing finding. One possibility is that the task demands of the single feature conditions are not directly comparable to the task demands involved in the binding conditions. Specifically, differences between these conditions exist in terms of the construction of the probe items; the lure probes in particular. In the single feature conditions, a target probe is a feature that was present in the preceding array, while a lure probe is a feature that was not present in the TBR array. As such correctly determining the answer is a simple matching task- “did I see this, or not?”. In the feature binding conditions, a target probe is constructed from features that were present in the preceding array and were shown as a combination; e.g. a red blob displayed in the top left corner in the array would be displayed as such again in the event of a target probe. A lure probe however is a novel combination of features that were both present in the TBR array but not shown together; e.g. that red blob may be shown in the bottom right location, a place that was previously occupied by a yellow blob. In the feature binding conditions then, correctly determining the answer is no longer a simple matching task, but instead relies on the memory of the relationships between the features rather than the memory of the features themselves. This difference in task demands may therefore drive the apparent ease with which participants remember combinations involving location, compared to their relatively poor memory for locations in isolation.

In addition to this, post experiment interviews with a number of participants also offered a potential explanation. A number of participants reported the mistaken belief that the black squares from which the structural mask is constructed represented the stimulus set of locations employed in the experiment. Thus, when the test probe was presented in the location feature task, participants were unsure as to whether the location had changed subtly between array and test. Whilst it is unknown how many participants misunderstood the role of the mask, it is possible that this interfering information may have led to poorer performance on this task. Due to the manner in which the probe items were constructed in the location binding conditions (colour-location, shape-location), this same logic may not have been applied by the participants further explaining the relative ease with which participants completed what should be a more difficult task. Thus, if performance on the location task was already impaired by the mask, then any true impact of cognitive load (this experiment) or maybe even cognitive ageing (Experiment 1) may too be masked (though it must again be noted that the bizarrely poor location task performance was not observed in Experiment 1, potentially making this finding an artefact of this specific population). Experiment 3 replicated Experiment 2 with the structural mask removed.

2.4 Experiment 3: Binding and Cognitive Load

2.4.1 Method

2.4.1.1 Participants

Thirty nine younger adults (20 female) from the student population of Bournemouth University and the local area, aged 19-27 years (*M* = 21.27, *SD* = 1.92) completed this study which lasted for approximately one hour. All participants received either course credit or an honorarium for participation and had normal or corrected-to-normal vision.

2.4.1.2 Materials

Stimuli and apparatus were identical to Experiment 2 with the exception that the structural mask was removed and the blank screen displayed during the retention interval, displayed for longer in order to maintain a consistent retention interval with the earlier experiments.

2.4.1.3 Design

The design was as described for Experiment 2.

2.4.1.4 Procedure

The procedure was as described for Experiment 2 but without the structural mask. The retention interval was again 900ms.

2.4.1.5 Data Analysis

As in Experiment 2, accuracy performance (d') was calculated for each binding condition and analysed with one 6 (task type) X 2 (cognitive load) repeated measures ANOVA, and by three separate 3 (task type) x 2 (cognitive load) repeated measures ANOVAs targeted at our specific predictions.

2.4.2 Results

Omnibus Analysis: A 6 (task type: colour, shape, location, colour & shape, colour & location, shape & location) x 2 (load: low, high) ANOVA for repeated measures revealed a significant main effect of task type, F (5,190) = 20.95, MSE = 9.90, p < .001, $\eta p^2 = .36$, $BF_{10} = 1.76^{e+17}$; see Table 2.3. for descriptive statistics, and post-hoc comparisons; with comparisons described in depth for each of the more targeted analyses. There was a significant detrimental effect of load, F (1,38) = 55.84, MSE = 25.59, p < .001, $\eta p^2 = .60$, $BF_{10} = 1.23^{e+10}$ (low load: M = 2.11, SD = 0.30; high load M = 1.64, SD = 0.37); and no significant interaction between factors, F (5,190) = 1.13, MSE = 0.36, p = .35, $\eta p^2 = .03$, $BF_{10} = 0.04$.

Table 2.3. Descriptive statistics and post-hoc comparisons exploring the main effect of task type in Experiment 3.

			Comparisons (df=38) t-statistic (BF_{10})					
Task Type	Mean	Standard Deviation	Colour	Shape	Location	Colour & Shape	Colour & Location	Shape & Location
Colour	2.39	0.53	-	8.65** (6.34e+8)	2.58* (3.10)	9.70** (1.15e+10)	3.80** (55.78)	6.28** (66023)
Shape	1.59	0.62	-	-	3.55** (29.62)	1.71 (0.65)	3.68** (41.44)	1.05 (0.29)
Location	2.08	0.71	-	-	-	5.16** (2437.56)	0.41 (0.19)	3.55** (29.81)
Colour & Shape	1.44	0.63	-	-	-	-	5.33** (4036.12)	2.81** (5.05)
Colour & Location	2.03	0.69	-	-	-	-	-	3.58** (31.67)
Shape & Location	1.72	0.57	-	-	-	-	-	-

*p < .05
**p < .01

Colour-Shape Binding: A 3 (task: colour, shape, combination) x 2 (load: low, high) ANOVA for repeated measures indicated a significant main effect of task, F (2,76) = 23.13, MSE = 12.77, p< .001, ηp^2 = .38, BF_{10} =1.40^{e+9}; whereby the colour task (M = 2.39, SD = 0.53) produced better performance than the shape task (M = 1.59, SD = 0.62; t(38)=8.65, p <.001, d = 1.39, BF_{10} = 6.44^{e+8}), and the colour-shape combination task (M = 1.44, SD = 0.63; t(38)=9.69, p <.001, d = 1.63, BF_{10} = 1.12^{e+10}); and the shape task produced better performance than colour-shape combination task, t(38)=1.71, p =.05, d = 0.24, BF_{10} = 0.65). Additionally, there was a significant main effect of load, F (1,38) = 24.47, MSE = 12.38, p < .001, ηp^2 = .39, BF_{10} = 4149.33) with low load (M = 2.00, SD = 0.77) yielding better performance than high load (M=1.61, SD=0.89), and no significant interaction between factors, $F(2,76) = 0.04$, $MSE = 0.01$, $p = 0.96$, $\eta p^2 = .001$, $BF_{10} = 0.08$). The data are presented in Figure 2.9.

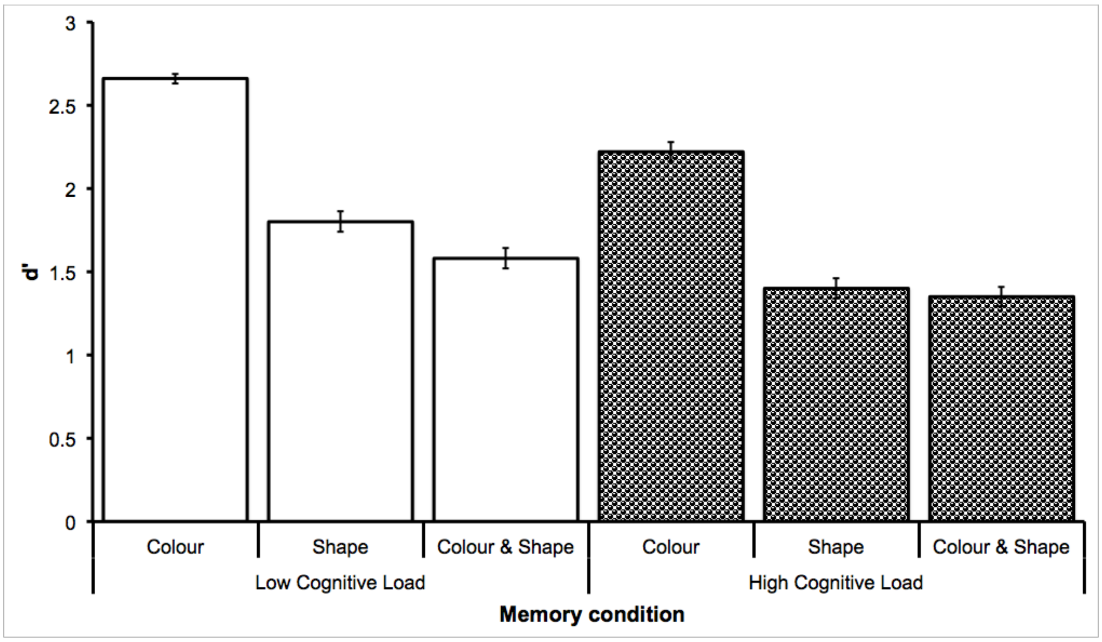


Figure 2.9. Plot showing d' scores for the colour and shape combination condition and its constituent features for each cognitive load condition in Experiment 3. Error bars represent standard error of the mean.

Colour-Location Binding: A 3 (task: colour, location, combination) x 2 (load: low, high) ANOVA for repeated measures indicated a significant main effect of task type, $F(2,76) = 44.63$, $MSE = 18.27$, $p < .01$, $\eta p^2 = .54$, $BF_{10} = 2.38^{e+14}$; whereby performance in the colour task ($M=2.39$, $SD=0.53$) was better than the location task ($M = 2.08$, $SD = 0.71$; $t(38) = 2.57$, $p = .01$, $d = 0.49$, $BF_{10} = 3.04$) and the colour-location task, ($M = 2.03$, $SD = 0.69$; $t(38) = 3.79$, $p < .001$, $d = 0.59$, $BF_{10} = 54.76$); while the location task did not differ to the colour-location task ($t(38)=0.42$, $p =.34$, $d = 0.07$, $BF_{10} = 0.19$). There was further a significant disruptive effect of load, $F(1,38) = 48.96$, $MSE = 12.38$, $p < .001$, $\eta p^2 = .56$, $BF_{10} = 4446.46$, (low load: M = 2.43, SD = 0.70; high load: M = 1.90, SD = 0.86) and no significant interaction between factors, $F(2,76) = 1.21$, $MSE = 0.36$, $p = .304$, $\eta p^2 = .03$, $BF_{10} = 0.59$). The data are presented in Figure 2.10.

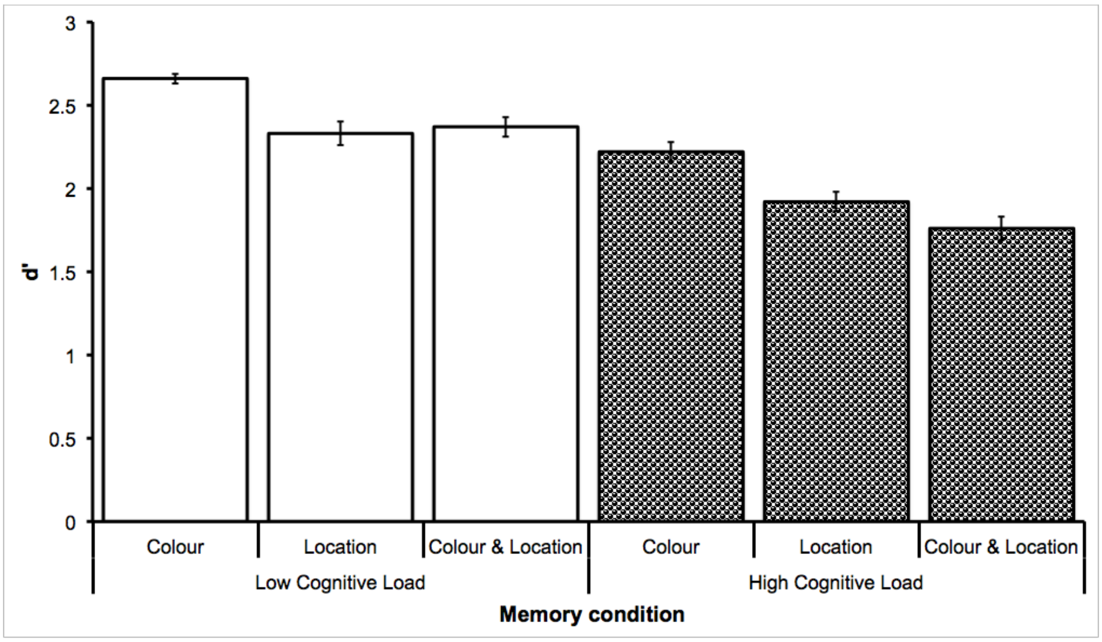


Figure 2.10. Plot showing d' scores for the colour and location combination condition and its constituent features for each cognitive load condition in Experiment 3. Error bars represent standard error of the mean.

Shape-Location Binding: A 3 (task: shape, location, combination) x 2 (load: low, high) ANOVA for repeated measures indicated a significant main effect of task type, $F(2,76) = 3.64$, $MSE = 1.55$, $p = .03$, $\eta p^2 = .09$, $BF_{10} = 1.14$; whereby performance in the shape task (M=1.59, SD=0.62) was less accurate than in the location task (M = 2.08, SD = 0.71; $t(38)=3.56$, $p <.001$, $d = 0.74$, $BF_{10} = 29.96$), while performance in the location task was superior to that in the shape-location task (M = 1.72, SD = 0.57; $t(38)=3.56$, $p <.001$, $d = 0.56$, $BF_{10} = 30.21$). Performance in the shape task did not differ to that in the shape-location task,

$t(38) = 1.04$, $p = .15$, $d = 0.22$, $BF_{10} = 0.29$. There was a significant detrimental effect of load, $F(1,38) = 21.07$, $MSE = 9.846$, $p < .001$, $\eta p^2 = .36$, $BF_{10} = 13234.98$, (low load: $M = 2.03$; $SD = .77$; high load: $M = 1.56$, $SD = .80$); and no significant interaction between factors, $F(2,76) = 1.58$, $MSE = 0.45$, $p = .21$, $\eta p^2 < .01$, $BF_{10} = 0.22$. The data are presented in Figure 2.11.

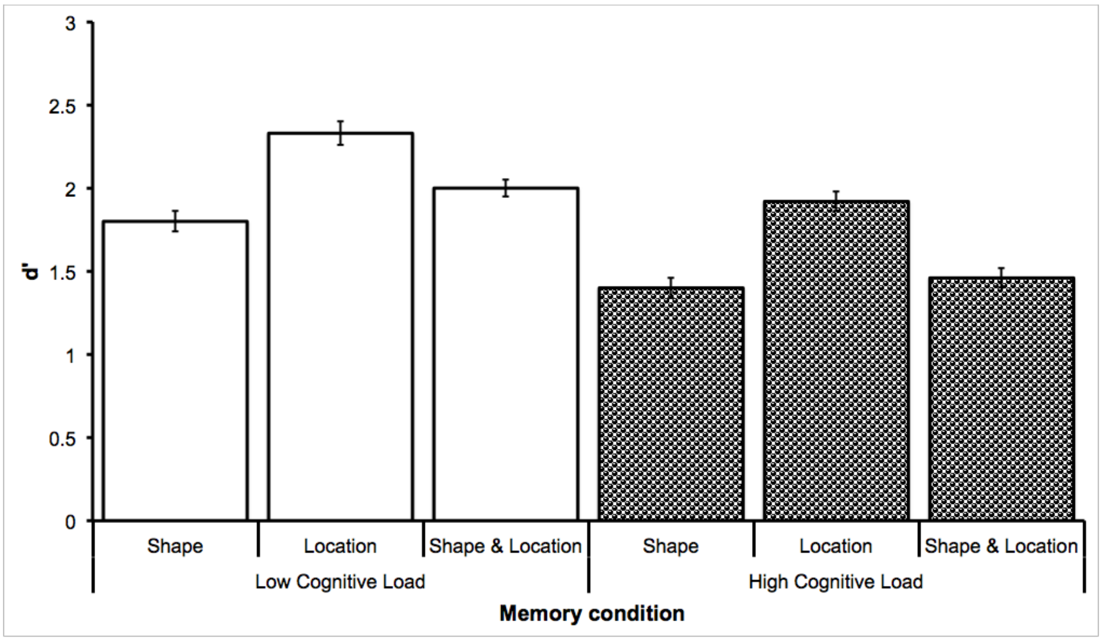


Figure 2.11. Plot showing d' scores for the shape and location combination condition and its constituent features for each cognitive load condition in Experiment 3.

Thus, with the removal of the mask, Experiment 3 again shows no specific deficit of either surface-feature binding or location binding as a function of cognitive load. The uniform deficit across all memory conditions under higher cognitive load is revealing itself to be a robust finding.

2.4.3 Discussion

Experiment 3 examined the effect of load on binding following the removal of the structural mask. In the absence of the mask, the location condition returned the highest accuracy of any memory condition as would be expected. The omnibus analysis in Experiment 3 showed a general decline in memory performance across all task types as a function of cognitive load. This is consistent with a division of attentional resources. Importantly, across the three experiments presented in Chapter 2, there has been an absence of interaction between task type and cognitive load. The absence of an interaction is of interest for two reasons. First, it suggests that feature binding occurs with relative automaticity in working memory, extending the findings of Allen et al. (2006) and Brown and Brockmole (2010) from surface-feature binding to location binding. Second, one might tentatively suggest that the lack of any specific decline in memory performance as a function of healthy ageing (revealed by the lack of any interactions between the age and memory condition factors) may be explainable in terms of reduction in working memory function. As before, specific comparisons between each feature type will be discussed separately in order to provide clear comparability with Brown and Brockmole (2010) who devised the paradigm from which our paradigm is adapted.

Experiment 3 replicated the two critical findings of Experiment 2. First, analyses of the surface feature binding condition again indicated that surface-feature binding is not disproportionately affected by manipulations of cognitive load. In other words, surface-feature binding appears to be a process that is undertaken in a relatively automatic manner, not drawing on attentional resources beyond those ascribed to the maintenance of individual features (Allen et al., 2006; Allen et al., 2012). The more difficult of the component features, shape, was shown to be slightly easier than the combination of colour and shape. This was in contrast to Experiment 2 where there was no difference between these conditions. Despite this apparent cross-experiment difference, it should be noted that the effect size for the shape and shape-colour combination comparison was very similar across the two experiments (d=0.20 and 0.24 for Experiments 1 and 2, respectively). Moreover, the modest size of these effects further supports the notion that surface-feature binding proceeds relatively automatically in working memory.

Second, the critical interaction between task type and load was absent for both location-binding conditions (colour-location; shape-location) suggesting that location binding is also not more affected by cognitive load than memory for the component single features. The comparisons in both location binding conditions indicated that memory for bound combinations of objects and locations are no more demanding on cognitive resources than memory for the most difficult of the constituent features. In Experiment 2, performance on the 'locations only' feature tasks was comparatively poor relative to the other single feature conditions – a finding that would not be predicted by existing research on memory capacity for visual features versus spatial locations (Luck & Vogel, 1997; Simons, 1996). In the absence of the mask, the results of Experiment 3 serve to replicate those reported by Allen et al. (2006; 2012) in suggesting that surface-feature binding is not disrupted by an attentionally demanding secondary task any more than memory for individual features. In addition, the findings of Experiment 3 extend existing research in suggesting that location binding too, at least as assessed using the current paradigm, is a process that proceeds relatively automatically.

2.5 Experiment 4: Binding and Cognitive Load

Before firm conclusions can be reached with regard to the automaticity of surface-feature binding and location binding, there is one more possibility that needs to be addressed. Specifically, one feature of the design of Experiments 2 and 3 (inherent in the paradigm as devised by Allen et al., 2006) was that the nature of change for irrelevant features varied differentially across task conditions – specifically, there were more changes in irrelevant features in the colour, shape and combination tasks than there were in the two location binding conditions. In each the colour, shape and combination blocks, the probe always appeared in a neutral location (the centre of the screen) meaning that the locations of the items changed between array and test. There were however no irrelevant feature changes between display and test in the two location binding conditions of this task as the alternate "third" surface feature was never displayed in that block (e.g. in the colour and location block, none of the shapes were present).

Although the procedures used in Experiments 1-2 closely followed an established method (Allen et al., 2006; Allen et al., 2012), subsequent research suggests that changes in spatial location between display and test, although irrelevant to the task, may be disruptive to the maintenance of surface-feature bindings (Logie, Brockmole, & Jaswal, 2011). Across three experiments, Logie et al. (2011) tested the effects of a task irrelevant change in location (Experiment 1), shape (Experiment 2), and colour (Experiment 3) on memory for the bound combinations of remaining features. Irrelevant changes in the surface features (colour /shape) were shown to be disruptive to correct recall upon immediate test, but this effect diminished rapidly with longer test intervals (i.e. performance in the no change and change conditions were comparable when the test interval was extended to 500ms). A task irrelevant change in location however, was disruptive to correct recall at immediate test and remained disruptive with test intervals of 500ms, with a small effect still present after 1000ms. Given that the paradigm used in this chapter has a test interval of 900ms it is possible that the surface-feature binding condition is being adversely, and specifically, affected by the change in the irrelevant location feature. Accordingly, Experiment 4 sought to control for this limitation by ensuring that the probe was changed to include only the feature(s) being tested in that block (following more closely the adapted procedures of Brown & Brockmole, 2010). Using this adapted procedure, Brown and Brockmole (2010) found (albeit limited) evidence supporting the idea that surface feature binding performance declined with age; thus, this method may maximise the opportunity for observing any impact of concurrent load.[2]

[2] Note that Allen et al. (2012) explained this discrepancy in terms of Brown and Brockmole's (2010) use of A' in their analyses as opposed to the more established use of d' signal detection measures.

Accordingly, in Experiment 4 the memory array always consisted of colour-shape combinations appearing in distinct locations, and only the task instructions varied between blocks of trials (e.g., to remember only the colours, only the shapes, or their combination in the surface-feature binding tasks; or only the locations, the colours/shapes or their combination in the case of the location binding tasks). The probe then consisted of only the tested feature(s). So, for instance, the probe was a single coloured blob (colour only – neutral shape), a single shape with no colour fill (shape only – neutral colour) or a coloured shape (colour and shape combination). Thus between array and probe, the single feature conditions were subject to two irrelevant feature changes, and each combination condition was subject to changes in one irrelevant feature; balancing this possible confound as much as is possible across blocks. We also took steps to equate stimulus difficulty across dimensions by introducing a new set of hard to verbalise colours and shapes. If either type of binding does require greater attentional than the maintenance of individual features, this paradigm adaptation offers the greatest likelihood of identifying them empirically (see Figure 2.12 for a detailed explanation).

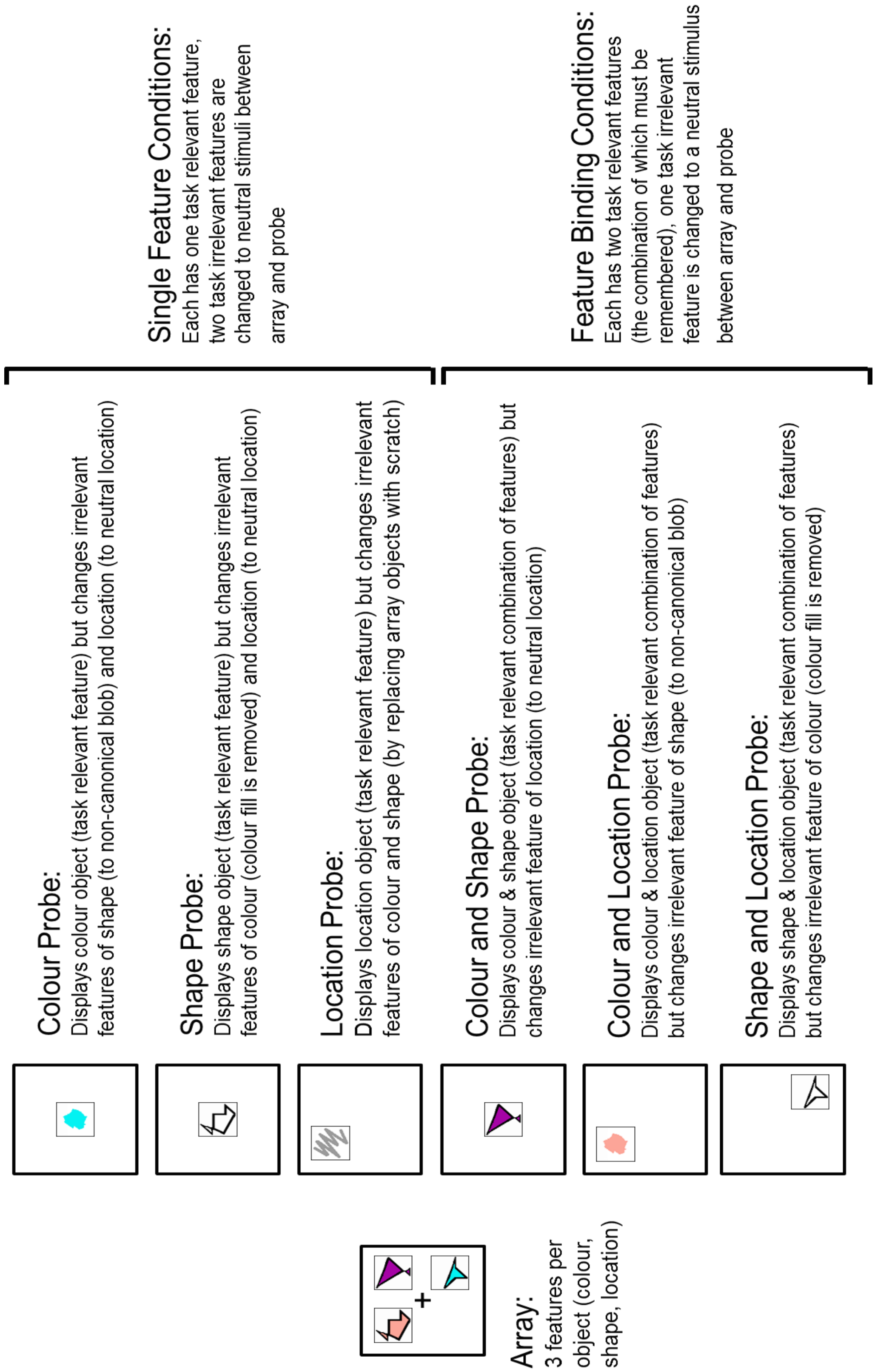


Figure 2.12. Detailed explanation of the feature changes between array and probe in Experiment 4.

2.5.1 Method

2.5.1.1 Participants

Eighteen younger adults (10 females, 8 males), aged 19-26 years (M = 21.33, SD = 1.81) completed this study which lasted for approximately 70 minutes. All participants received an honorarium for participation and had normal/ corrected to normal vision.

2.5.1.2 Materials

New stimuli were introduced for this study in an attempt to reduce the nameability of each stimulus (Figure 2.13). Non-standard polygon shapes were used along with colours previously shown to be difficult to name (colour 1; R-137, G-137, B-0, colour 2; R-0, G-235, B-235, colour 3; R-137, G-0, B-137, colour 4; R-255, G-219, B-0, colour 5; R-78, G-139, B-187, colour 6; R-250, G-137, B-124; Parra, Logie, Abrahams & Della Sala, 2009). Each stimulus was also made larger than in previous experiments to account for the increased complexity of these non-standard shapes (Figure 2.13). Each stimulus was now presented within a l.87°xl.87° frame (note these sizes are approximate due to an unconstrained viewing angle) with the size of the stimulus itself scaled to match. The location set was as in previous experiments.

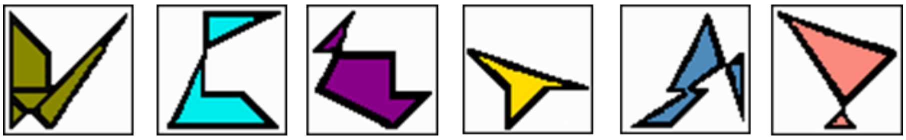


Figure 2.13. Example stimuli. Each shape could appear in any of the six colours. Each feature sampled without replacement within a given trial. Note that locations remained unchanged from previous experiments in this chapter.

2.5.1.3 Design

The design was as described for Experiments 2 and 3.

2.5.1.4 Procedure

The procedure closely followed that described for Experiment 3. The TBR array consisted of three coloured shapes appearing in distinct locations in all conditions. Participants were instructed as to what they should remember about the TBR at the start of each block of trials (e.g. "In this block, you should remember the **colours** of the objects presented"). The probes were consistent with those used in Experiments 1-3 showing only the task relevant feature - e.g. in the colour only block the array was three coloured shapes each in a unique location, while the probe was a non-canonical blob (neutral shape) of colour in a neutral location. This resulted in two irrelevant feature changes in each of the single feature blocks and one irrelevant feature change in the feature conjunction blocks better balancing the potential confounds of an irrelevant feature change that were noted in Experiment 3. Following pilot work involving the testing and interviewing of participants not included in the final analysis, the

TBR array was displayed for 900ms to allow for the increased complexity of the shape stimuli (Figure 2.14).

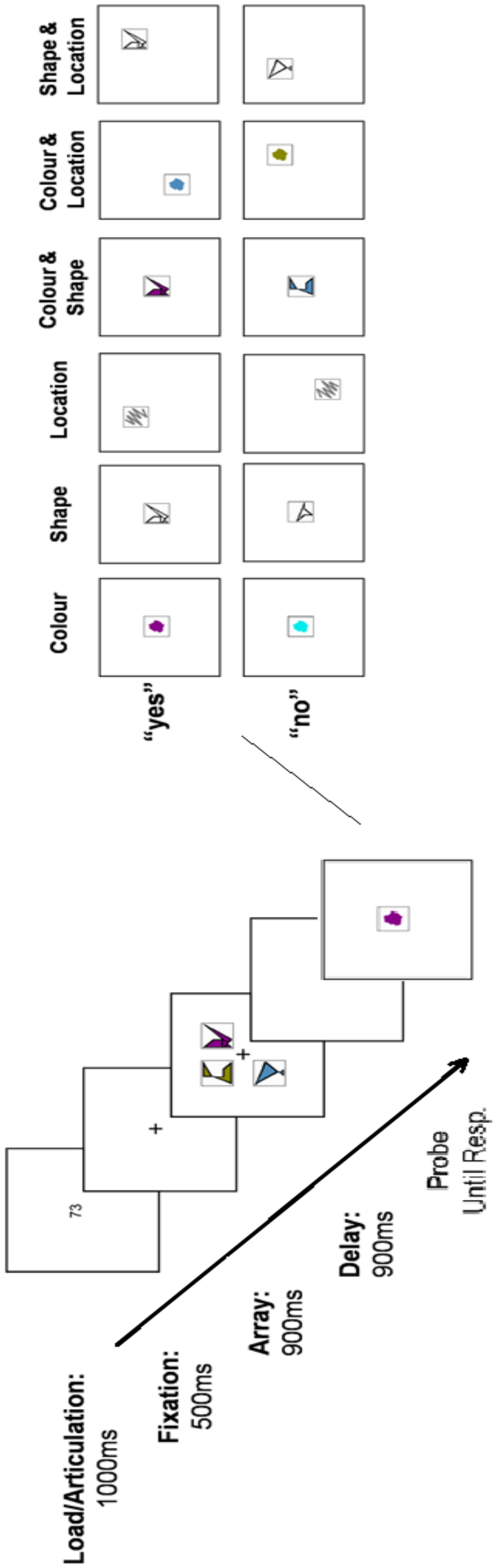


Figure 2.14. Trial procedure and example probes in each condition of Experiment 4

2.5.1.5 Data Analysis

As in Experiment 3, accuracy performance (d’) was analysed with one 6 (task type) X 2 (cognitive load) ANOVA, and additionally via the three separate 3 (task type) x 2 (cognitive load) repeated measures ANOVAs targeted towards our specific hypotheses.

2.5.2 Results

Omnibus Analysis: A 6 (task: colour, shape, location, colour & shape, colour & location, shape & location) x 2 (load: low, high) ANOVA for repeated measures revealed a significant main effect of feature type, $F(5,85) = 45.35$, $MSE = 21.5$, $p < .001$, $\eta p^2 = .73$, $BF_{10} = 1.77^{e+25}$); see table 2.4. for descriptive statistics, and post-hoc comparisons (comparisons described in detail with each of the targeted analyses). There was a significant detrimental effect of load, $F(1,17) = 18.783$, $MSE = 21.06$, $p < .001$, $\eta p^2 = .53$, $BF_{10} = 2760.76$ (low load: $M = 2.36$, $SD = 0.98$; high load $M = 1.74$, $SD = 1.09$); and no significant interaction between factors, $F(5,85) = 0.20$, $MSE = 0.72$, $p = .96$, $\eta p^2 = .01$, $BF_{10} = 0.03$.

Table 2.4. Descriptive statistics and post-hoc comparisons exploring the main effect of Feature type in Experiment 4.

			Comparisons (df=17) t-statistic (BF_{10})					
Task Type	Mean	Standard Deviation	Colour	Shape	Location	Colour & Shape	Colour & Location	Shape & Location
Colour	2.60	0.59	-	13.57** (5.81e+7)	1.74 (0.85)	6.55** (4100.07)	0.5 (0.27)	5.05** (282.72)
Shape	0.78	0.38	-	-	16.51** (1.08e+10)	6.94** (7956.43)	8.74** (137480)	6.59** (4425)
Location	2.87	0.47	-	-	-	7.54** (21847.88)	1.80* (0.92)	6.04** (1740)
Colour & Shape	1.64	0.51	-	-	-	-	5.11** (321.00)	1.45 (0.59)
Colour & Location	2.51	0.81	-	-	-	-	-	3.56** (17.80)
Shape & Location	1.89	0.70	-	-	-	-	-	-

*p < .05
**p < .01

As before, each class of binding (colour-shape; shape-location; colour-location) was also assessed through three separate 3 (Feature) X 2 (Load) ANOVAs conducted on accuracy measures based on d' estimates.

Surface-Feature Binding: A 3 (task: colour, shape, combination) x 2 (load: low, high) ANOVA for repeated measures revealed a significant main effect of feature type, $F(2,34) = 90.39$, $MSE = 0.33$, $p < .001$, $\eta p^2 = .84$, $BF_{10} = 1.06^{e+18}$; whereby performance was better in the colour task (M=2.60, SD=0.59) relative to the shape task (M = 0.78, SD = 0.38; $t(17) = 13.53$, $p < .001$, $d = 3.67$, $BF_{10} = 5.81^{e+8}$) and the colour-shape task (M = 1.64, SD = 0.51; $t(17) = 6.54$, $p < .001$, $d = 1.74$, $BF_{10} = 4100.00$), while the shape task was more difficult than colour-shape task, $t(17) = 6.93$, $p < .001$, $d = 1.92$, $BF_{10} = 7956.00$). There was a significant detrimental effect of load, $F(1,17) = 36.57$, MSE = 0.30, $p<.001$, $\eta p^2 = .68$, $BF_{10} = 46.68$ (low load: M = 2.00, SD = 1.36; high load M = 1.36, SD = 0.96); and no significant interaction between factors, $F(2,34) = 0.16$, MSE = 0.31, $p=.850$, $\eta p^2 = .01$, $BF_{10} = 0.16$. The data are illustrated in Figure 2.15.

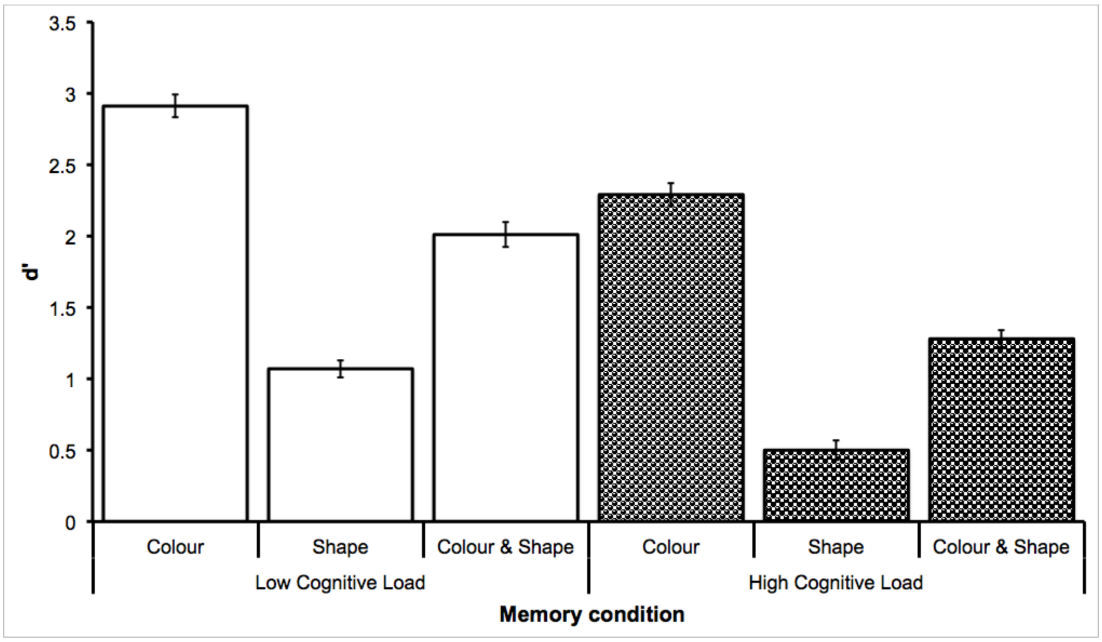


Figure 2.15. Plot showing d' scores for the colour and shape combination condition and its constituent features for each cognitive load condition in Experiment 4.

Colour-Location Binding: A similar 3 (task: colour, location, combination) x 2 (load: low, high) ANOVA for repeated measures indicated no significant main effect of feature type, $F(2,34) = 2.14$, MSE = 0.58, $p=.134$, $\eta p^2 = .11$, $BF_{10} = 0.55$, although the Bayes Factor here is insensitive, a significant negative impact of load, $F(1,17) = 15.82$, MSE = 0.60, $p < .01$, $\eta p^2 = .48$, $BF_{10} = 1133.19$, (low load: M = 2.96, SD = 0.87; high load: M =2.37, SD=0.87) and no significant interaction between factors, $F(2,34) = 0.37$, $MSE = 0.27$, $p = 0.695$, $\eta p^2 = .02$, $BF_{10} = 0.16$. The data are presented in Figure 2.16.

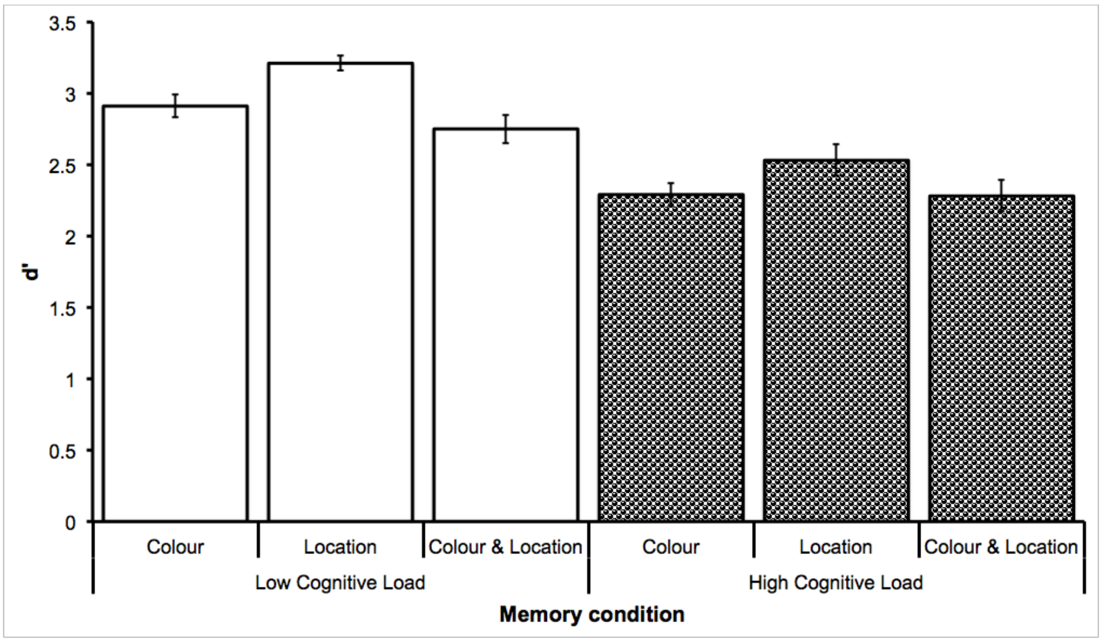


Figure 2.16. Plot showing d' scores for the colour and location combination condition and its constituent features for each cognitive load condition in Experiment 4.

Shape-Location Binding: A final 3 (task: shape, location, combination) x 2 (load: low, high) ANOVA for repeated measures indicated a significant main effect of feature type, $F(2,34) = 92.71$, $MSE = 0.42$, $p < .001$, $\eta p^2 = .85$, $BF_{10} = 2.03^{e+16}$, whereby the shape task ($M=0.78$, $SD=0.38$) was more difficult than the location task ($M=2.87$, $SD=0.47$; $t(17) = 16.50$, $p < .001$, $d = 4.89$, $BF_{10} = 1.08^{e+10}$), and the shape-location task ($M=2.51$, $SD=0.82$; $t(17) = 6.58$, $p < .001$, $d = 2.71$, $BF_{10} = 4425$), while and the location task was easier than shape-location task, $t(17) = 6.05$, $p < .001$, $d = 0.54$, $BF_{10} = 1741$. There was a significant negative impact of load, $F(1,17) = 9.74$, $MSE = 1.14$, $p < .01$, $\eta p^2 = .36$, $BF_{10} = 9.23$ (low load:

M=2.17, SD=1.07; high load M=1.53, SD=1.23); and no interaction between factors, $F(2,34) = 0.07$, $MSE = 0.45$, $p=.94$, $\eta p^2 < .01$, $BF_{10} = 0.15$. The data are presented in Figure 2.17.

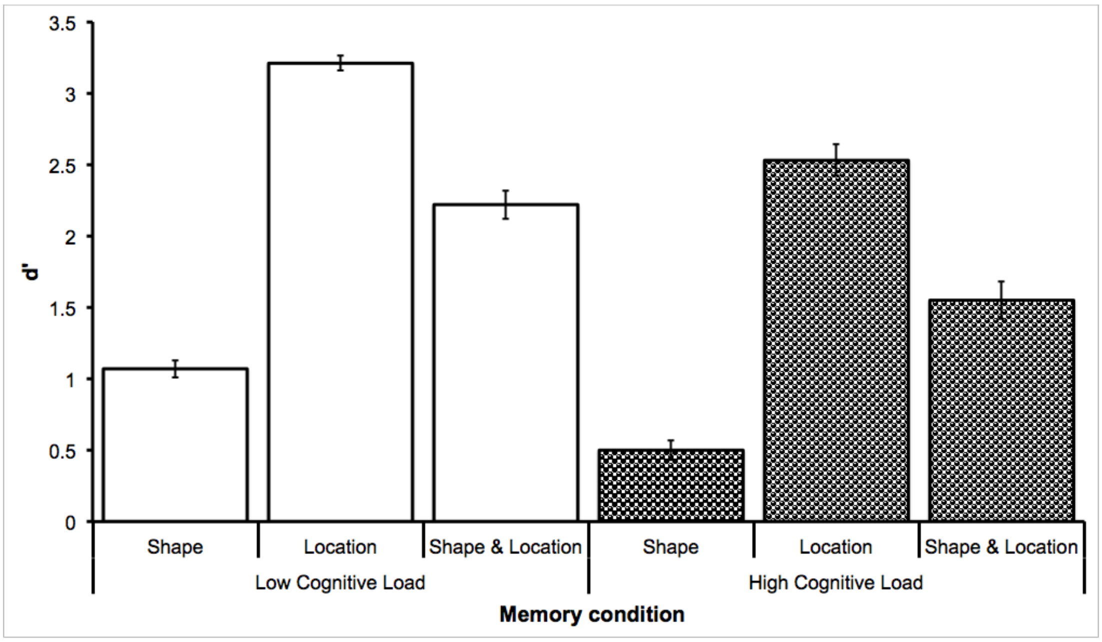


Figure 2.17. Plot showing d' scores for the shape and location combination condition and its constituent features for each cognitive load condition in Experiment 4.

In summary, even with the balanced changes in task irrelevant feature, cognitive load has no greater impact on feature binding processes than on memory for individual features.

2.5.3 Discussion

The aim of Experiment 4 was to assess the role of attentional resources during surface-feature binding and location binding while addressing a possible confound in terms of the number of task irrelevant features that changed between the array and probe inherent in the paradigm used in Experiments 1-3. The data again suggested that neither surface-feature binding nor location binding were specifically affected by a concurrent attentionally demanding task. Thus, surface-feature binding and location binding, as assessed by this paradigm, both appear to proceed relatively automatically in working memory.

Of note, the individual task type comparisons were affected by the difficulty of the shape condition, likely, an artefact of switching to hard-to-name visual features in this version of the paradigm. Where shape was a constituent single feature it was seen to be more difficult than the combination condition, as opposed to the previous experiments that broadly show the more difficult constituent feature to be equal in difficulty to its bound combination. Whilst counter-intuitive, this finding is consistent with the notion of neither class of feature binding being more demanding on attentional resources than memory for single features. A clearer display of this effect can be seen in the colour-location comparisons. Here the main effect of task type was non-significant, showing that the constituent features (colour and location) were of similar processing difficulty to one another, and equally difficult to the bound combination of colour and location. This serves as a clear demonstration that object to location binding, as it is measured by this paradigm, draws no more heavily on attentional resources than memory for single features because if it did one would expect an to find an interaction when analysing the location binding comparisons (e.g. the ANOVA for colour, location, and colour & location); whereby performance in the location binding condition would be more greatly reduced by the additional cognitive load of the backward counting task, than the single feature conditions were.

The methodological changes implemented in Experiment 4, (colour stimulus set, shape stimulus set, balanced irrelevant feature change) resulted in only one notable difference in the pattern of results between this and the previous experiments. The shape stimuli used here were clearly more difficult to hold in memory than the other single features (colour and location) resulting in far poorer recognition performance in the shape only task. The issue of differing task demands raised in the discussion of Experiment 2 may also offer an explanation as to why the apparent difficulty of the shape task is not present in the binding conditions involving shape (colour-shape, shape-location) here in Experiment 4. To reiterate, in Experiment 2 it was proposed that the task demands of the single feature conditions were not directly comparable to the task demands in the feature-binding conditions largely due to the nature of the lure probes. Specifically, in single feature conditions, the task becomes a simple case of "did I see this, or not?" while in the feature binding conditions successful completion of the task requires memory of the relationships between the features as all features present in the probe were present in the preceding array. This difference in task demands may therefore be the reason behind the apparent ease with which participants remember combinations involving shape, compared to their relatively poor memory for shapes as a single feature task. In addition, in this task adaptation, the arrays consisted of three coloured shapes in every condition (compared to arrays that only displayed the task relevant features in the previous task condition), participants may be drawn to the easier and more salient features of the array. While this salience is likely somewhat driven by the baseline difficulty of remembering each single feature, such an effect could potentially widen the task difficulty gap between the most difficult to remember single feature (in this experiment, shape), and easiest to remember single features (colour, location). In addition to being an intuitively appealing explanation, coloured objects have been shown as being among the easier features to detect in visual search tasks (Koivisto, Hyönä, & Revonsuo, 2004) further suggesting that attention may be drawn to colour over shape. An alternative explanation is the proposed automaticity with which features intrinsic to an object are bound together (Ecker et al., 2013), and the subsequent effects of an irrelevant feature change (Logie et al., 2011). Ecker et al. (2013) propose that when remembering shapes, participants implicitly bind the colours to those shapes as the colour is an intrinsic feature of the shape presented. As a result, the task-irrelevant change of colour that occurred in all shape task probes, combined with the task irrelevant change of location, would be detrimental to recall of the shapes. However, Logie et al. (2011) demonstrated that irrelevant changes of colour are not disruptive to object memory in the timeframes used in the present experiment. Also hampering this as a potential explanation, is that the difficulty Ecker et al. (2013) have in defining what constitutes an intrinsic feature (indeed, in their experiment, effects of intrinsic feature binding were most apparent when a 3 dimensional effect was applied to the shape). Therefore a final possible explanation, and by far the most parsimonious explanation, is simply that the abstract shapes in this task are particularly difficult to remember, relative to colours or locations, when three of them are presented on screen for just 900ms. It should also be acknowledged that the changes to the paradigm in Experiment 4, in particular the change to a full feature array (showing coloured shapes in every condition, irrespective of task condition), may have increased the likelihood of binding in all conditions. In the case that participants were unable, or had chosen not, to inhibit whichever of the features were not relevant to the task condition (for example, shapes would be irrelevant to the completion of the colour and location task), the irrelevant feature would likely be bound to the representations of the displayed objects that is held in memory. As such, performance in all conditions may have been negatively impacted by the additional cost of decomposing the object held in memory into the features present in the probe. This decomposition cost has previously been shown to reduce accuracy in change detection tasks (see Prabakaran et al, 2000, & Elsley & Parmentier, 2009, for examples of the decomposition cost in feature binding tasks).

In sum, Experiment 4 sought to address a confound in respect to the amount of information that changed between display and test for in single feature and combination conditions in the paradigm adaptation used in Experiments 1-3. While Experiment 4 has replicated the general detrimental effect of increased cognitive load on memory for both single features and bound combinations of features, it additionally confirms our earlier observation that there is no specific detrimental effect of concurrent load on either surface-feature binding or location binding. The final experiment in this chapter examined the impact of ageing on surface-feature binding and location binding in older adults using this task adaptation.

2.6 Experiment 5: Binding and Ageing - Balanced Irrelevant Feature Change

2.6.1 Method

2.6.1.1 Participants

There were 30 participants in total. Twenty younger adults (16 females, 4 males), aged 19-24 years (*M* = 20.84, *SD* = 1.85), with a mean number of years of education of 12.64 (*SD* = 0.64) and a mean verbal IQ, predicted by the WTAR of 114.8 (*SD* = 6.20). The older adult group consisted of 10 volunteers (7 females, 3 males), aged 65-74 years (*M* = 69.53, *SD* = 4.39), with a mean number of years of education of 11.54 (*SD* = 1.96) and a mean verbal IQ, predicted by the WTAR of 117.4 (*SD* = 6.63). Predicted verbal IQ was no different between younger and older adults ($t(28) = 1.27$, $p = .13$). Older adults were screened for atypical cognitive decline using the Montreal Cognitive Assessment (MoCA; Nasrendine et al., 2005) and again used the cut-off score of 23 (with scores lower than 23 being considered markers of mild cognitive impairment; Luis et al., 2009). The mean score on the MoCA across older adults was 27.21 (*SD* = 1.43) with no participants meeting the exclusion criteria. In addition, participants reported no significant memory problems and normal or corrected-to-normal vision. All participants received either course credit or an honorarium for participation and were naïve to the experimental aims.

2.6.1.2 Materials

The materials were as described for Experiment 4.

2.6.1.3 Design

Experiment 5 utilised the paradigm as in Experiment 4, though adopted a between subjects design (as described for Experiment 1); comparing the recognition performance of younger and older adults assessed using d' scores in six conditions (colour, shape, location, colour & shape, colour & location, shape & location). In addition to omnibus analysis, smaller analyses comparing each combination condition with its constituent features (e.g., colour, shape, and colour & shape) were conducted.

2.6.1.4 Procedure

The procedure was as described for Experiment 4 with the exception that there was no cognitive load condition. Instead, each participant completed each memory task once while repeating numbers out loud (serving as concurrent articulation).

2.6.1.5 Data Analysis

As in Experiments 3 and 4, accuracy performance (d') was calculated for each binding condition and analysed with one mixed design 6 (task type) X 2 (age)

ANOVA in addition to three separate mixed design 3 (task type) x 2 (age) repeated measures ANOVAs (with age group as a between subjects factor).

2.6.2 Results

Omnibus Analysis: A 6 (task: colour, shape, location, colour & shape, colour & location, shape & location) x 2 (age group: younger, older) mixed effects ANOVA revealed a significant main effect of task type, $F (5,130) = 37.97$, $MSE = 0.47$, $p < .001$, $\eta p^2 = .59$, $BF_{10} = 5.64e+24$); see table 2.5 for descriptive statistics, and post-hoc comparisons; with comparisons described in depth for each of the more targeted analyses. Younger adults were significantly more accurate than older adults, $F (1,26) = 23.34$, $MSE = .95$, $p < .001$, $\eta p^2 = .47$, $BF_{10} = 16.96$ (younger: $M = 2.52$, $SD = 1.12$; older $M = 1.75$, $SD = 1.07$); and there was no interaction between factors, $F (3,130) = 2.01$, $MSE = 0.47$, $p = .08$, $\eta p^2 = .07$, $BF_{10} = 1.08$.

Table 2.5. Descriptive statistics and post-hoc comparisons exploring the main effect of Feature type in Experiment 5.

			Comparisons (df=27) t-statistic (BF_{10})					
Task Type	Mean	Standard Deviation	Colour	Shape	Location	Colour & Shape	Colour & Location	Shape & Location
Colour	2.87	0.78	-	11.35** (1.00e+10)	0.17 (0.20)	7.05** (108753.79)	1.24 (0.40)	4.15** (98.38)
Shape	0.75	0.48	-	-	11.04** (5.57+e9)	4.87** (560.36)	12.64** (1.03e+11)	7.26** (180469)
Location	2,91	0.95	-	-	-	5.16** (1136.75)	0.63 (0.24)	3.04** (7.96)
Colour & Shape	1.76	0.95	-	-	-	-	8.89** (7.06e+7)	2.31* (1.93)
Colour & Location	3.02	0.77	-	-	-	-	-	4.86** (552.99)
Shape & Location	2.18	0.96	-	-	-	-	-	-

*p < .05
**p < .01

As with the data analyses in previous experiments, the data from each class of binding (colour-shape; shape-location; colour-location) in Experiment 5 was also assessed through three separate 3 (Feature) x 2 (age) ANOVAs conducted on accuracy measures based on d' estimates.

Colour-Shape Binding: A 3 (task: colour, shape, combination) x 2 (age group: younger, older) mixed effects ANOVA indicated a significant main effect of task, F (2,52) = 58.41, MSE = 0.43, p< .001, ηp^2 = .69, BF_{10} = 5.30e+15; whereby the colour task (M = 2.87, SD = 0.78) produced better performance than the shape task (M = 0.75, SD = 0.48), and the colour-shape combination task (M = 1.76, SD = 0.95); and the colour-shape combination task produced better performance than the shape task (see table 2.5 for comparison statistics). There was a significant main effect of age group, F (1,26) = 12.41, MSE = 0.56, p < .001, ηp^2 = .

32, BF_{10} = 1.35, with younger adults (M = 2.01, SD = 1.17) producing more accurate performance than older adults (M=1.30, SD=1.04), and a significant interaction between factors, F (2,52) = 3.90, MSE = 0.43, p = .03, ηp^2 = .13, BF_{10} = 3.97. Exploratory analyses indicate that the interaction is explainable by the comparative lack of difference between younger and older adults in the shape condition (younger M = 0.77, SD = 0.36, older M = 0.74, SD = 0.67; t(26) = 0.13, p = .90, d = 0.66, BF_{10} = 0.37) relative to the difference shown in the colour (younger M = 3.23, SD = 0.53, older M = 2.23, SD = 0.77; t(26) = 4.07, p < .001, d = 1.82, BF_{10} = 65.78;) and colour & shape conditions (younger M = 2.04, SD = 0.81, older M = 1.27, SD = 1.02; t(26) = 2.20, p < .01, d = 0.82, BF_{10} = 2.01). The data are presented in Figure 2.18.

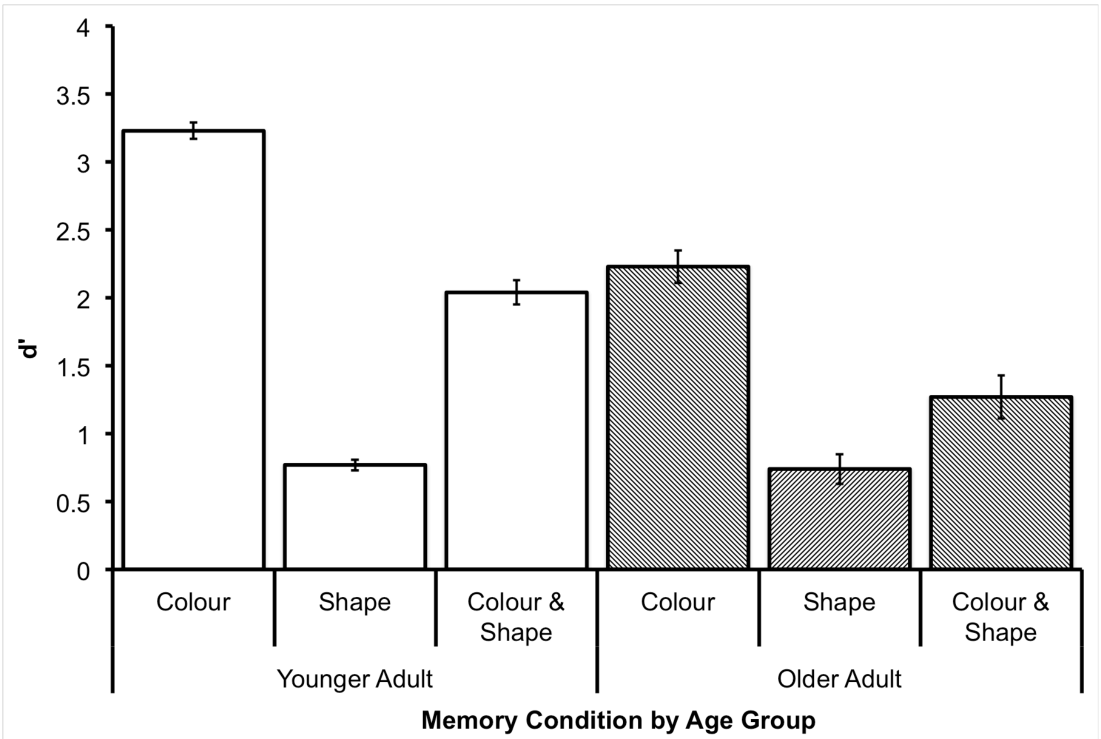


Figure 2.18. Plot showing d' scores for the colour and shape combination condition and its constituent features for each age group in Experiment 5. Error bars represent standard error of the mean.

Colour-Location Binding: 3 (task: colour, location, combination) x 2 (age: young, old) mixed effects ANOVA indicated no significant main effect of feature type, F (2,52) = 0.45, MSE = 0.44, p = .64, ηp^2 = .02, BF_{10} = 0.15, a significant negative impact of age, F(1,26) = 33.93, MSE = 0.56, p < .001, ηp^2 = .57, BF_{10} = 1634.55 (younger: M = 2.52, SD = 0.50; older: M = 2.29, SD = 0.93) and no significant interaction between factors, F (2,52) =0.15, MSE = 0.44 p = .86, ηp^2 = .01, BF_{10} = 0.20. The data are presented in Figure 2.19.

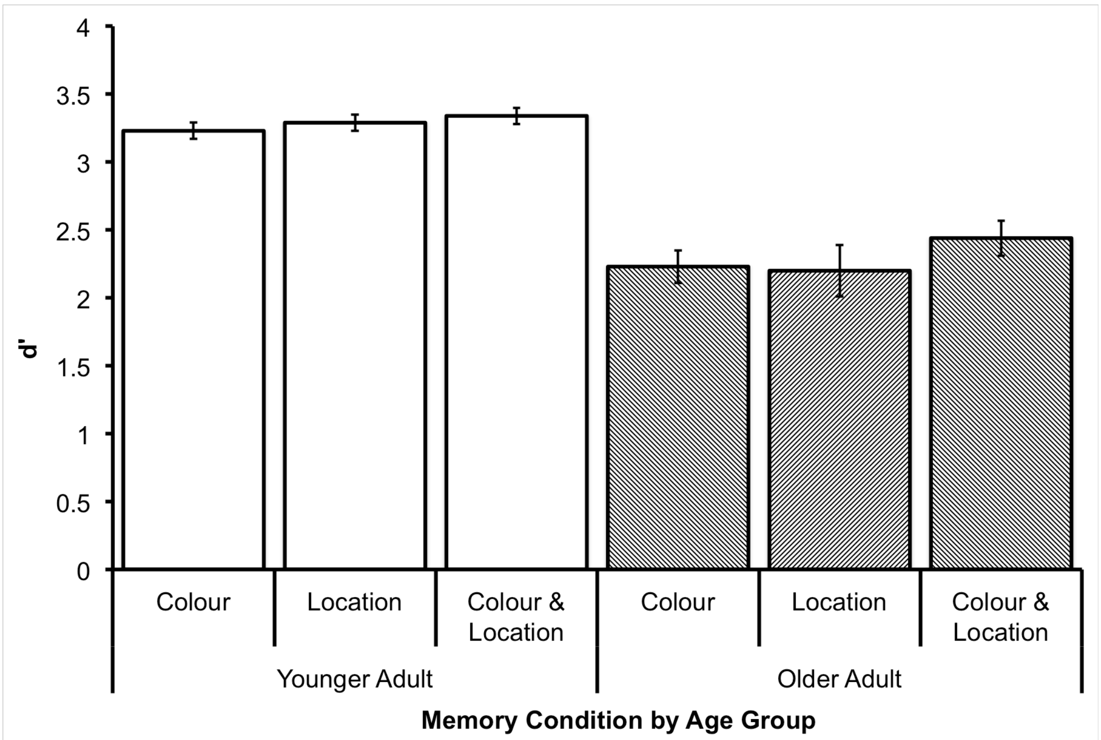


Figure 2.19 Plot showing d' scores for the colour and location combination condition and its constituent features for each age group in Experiment 5. Error bars represent standard error of the mean.

Shape-Location Binding: A final 3 (task: shape, location, combination) x 2 (age group: younger, older) mixed effects ANOVA with age as a between subjects factor indicated a significant main effect of task, F (2,52) = 46.15, MSE = 0.57,

$p < .001$, $\eta p^2 = .64$, $BF_{10} = 1.94e+14$; with the shape task (M = 0.75, SD = 0.48) producing poorer performance than the location task (M = 2.91, SD = 0.95), and the shape-location combination task (M = 2.18, SD = 0.96); and the location task produced better performance than the shape-location combination task (comparison statistics in table 2.5). There was a significant main effect of age group, $F(1,26) = 14.13$, $MSE = 0.54$, $p < .001$, $\eta p^2 = .35$, $BF_{10} = 1.31$, with younger adults (M = 2.17, SD = 1.24) producing more accurate performance than older adults (M=1.52, SD=1.10), and a significant interaction between factors, $F(2,52) = 3.36$, $MSE = 0.57$, $p = .04$, $\eta p^2 = .12$, $BF_{10} = 2.82$. The interaction again best explained by the comparative lack of difference between younger and older adults in the shape condition (shape: younger M = 0.77, SD = 0.36, older M = 0.74, SD = 0.67; $t(26) = 0.13$, $p = .90$, $d = 0.66$, $BF_{10} = 0.37$; location: younger M = 3.30, SD = 0.50, older M = 2.20, SD = 1.18; $t(26) = 3.46$, $p < .01$, $d = 1.47$, $BF_{10} = 18.42$; shape & location: younger M = 2.45, SD = 0.94, older M = 1.69, SD = 0.81; $t(26) = 2.17$, $p = .04$, $d = 0.85$, $BF_{10} = 1.90$). The data are presented in Figure 2.20.

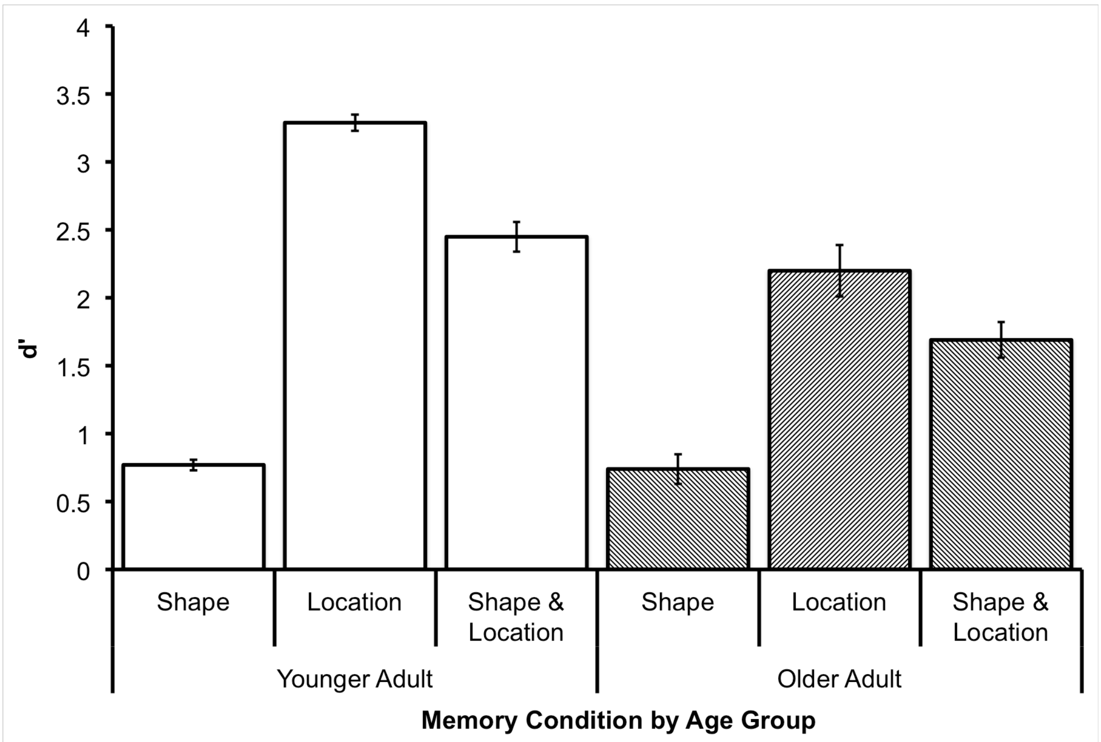


Figure 2.20. Plot showing d' scores for the shape and location combination condition and its constituent features for each age group in Experiment 5.

Performance here mirrored that of Experiment 1 in showing no specific age related binding deficit in either surface-feature binding or location binding ability. Although older adult performance was worse overall, with again any difference uniform across all memory conditions.

2.6.3 Discussion

The aim of Experiment 5 was to assess surface-feature binding and location binding across younger and older adults using the task adaptation devised to balance changes in irrelevant features in Experiment 4. As in Experiment 1, we aimed to assess two hypotheses; The *ageing-context hypothesis*, whereby ageing is predicted to detrimentally affect location binding ability due to declines in context-association ability (Meulenbrock et al., 2010), and the *ageing-attention hypothesis*, whereby changes to feature binding ability as a factor of ageing are explainable in terms of reduced attentional resources. The findings of Experiment 5 replicated those of Experiment 1 in showing that neither surface-feature binding nor location binding was specifically impaired in the older adult sample (although younger adults did outperform older adults overall).

The omnibus analysis indicated a significant interaction between age group and visual memory task type which appeared to be driven by a lack of performance difference between younger and older adults in the shape memory task only. This lack of difference is likely due to the relative difficulty of the shapes condition, with performance across both groups approaching floor (though notably performance remained above chance for both younger and older adults groups).

As with the omnibus analysis, specific analyses targeted at investigating each type of binding individually (colour -shape; shape-location; colour -location) across age groups failed to indicate any binding deficits as a function of healthy ageing (with interactions that were present explainable by the relative lack of difference between the two groups in the shapes task). On this basis, the ageing context hypothesis does not find any support. Indeed, across two experiments we have failed to find any evidence to suggest that older adults show impairment in either type of binding, never-mind a deficit specific to location binding.

It is possible that the experimental paradigm adopted so far investigates only one facet of binding performance – that is, intentional binding, under explicit instructions to remember combinations of features. In order to fully understand older adult's binding performance (and explore the ageing-attention hypothesis and the ageing-context hypothesis) more fully, it is desirable to also assess binding performance under incidental encoding instructions. This issue is discussed in greater depth below, and additionally forms the basis of Chapter 3.

2.7 Chapter Two General Discussion

Chapter 2 investigated surface-feature binding and location binding across younger and older adults, with an aim to contrast two hypotheses: *The ageing-context hypothesis* which predicted that older adults may be specifically impaired in their memory for objects in locations (colour & location, shape & location), relative to their memory for single features (colour, shape, location) or surface-feature combinations (colour & shape). Alternatively, the *ageing-attention hypothesis* suggests that any deficit in binding in older adults may be attributed to a general decline in attentional functioning during ageing (e.g.

Sylvain-Roy et al., 2005). This hypothesis predicts binding impairments in older adults for any class of binding that draws on attentional resources. Indeed, if the ageing-attention hypothesis is correct, it should be possible to mimic older adult performance in younger adults when the latter undertake a binding task in the presence and absence of a concurrent load.

Experiment 1 failed to support the *ageing context hypothesis.* Although older adult performance was worse than that of younger adults overall, this effect was uniform across memory task conditions and not specific to those including location biding (colour -location task; shape-location task). Although there was no evidence of an age-related binding deficit in Experiment 1, the ageing-attention hypothesis was not challenged by these data. This hypothesis predicted binding deficits in older adults in circumstances where the binding task in question draws on attentional resources. Under this hypothesis, older adults should not be impaired on binding tasks which processed relatively automatically in working memory. Indeed, the attentional requirement for surface-feature binding and location binding is an empirical question, which was addressed in Experiment 2, which replicated the procedures of Experiment 1 but assessed performance only in younger adults under conditions of concurrent articulation and backwards counting (Allen et al., 2006 – low and high cognitive load, respectively). The findings from Experiment 2 indicated that while cognitive load impaired performance overall, this was again uniform across memory tasks (i.e., not specific to conditions requiring binding) suggesting that both surface-feature binding and location biding, at least as measured using this paradigm, proceed relatively automatically in the workspace of working memory.

Experiment 2 further produced an unexpected finding in the location only single feature task. Here, performance was much worse than the other single feature conditions. It transpired during post-experiment interview that at least some of the participants were unsure about the nature of the structural mask that was used in this task, and whether or not the locations indicated in this mask also corresponded to the potential locations of the probe. To explore the possibility that the mask may have had a negative, specific effect on the locations condition, and in an effort to level up performance across feature conditions, Experiment 3 replicated Experiment 2 with the structural mask removed.

The findings of Experiment 3 (along with having the desired effect of bringing performance in the location condition into line with what was initially expected in Experiments 1 & 2) replicated those of Experiment 2, in that while attention reduced performance overall, this decline was not specific to any of the binding conditions. Following the completion of Experiment 3, we observed that our task adaptation had some potentially confounding variations across feature and binding conditions, whereby the number of irrelevant feature changes varied between task type conditions. We addressed this in Experiment 4 which included a modification to the paradigm which sought to address a possible confound in the number of irrelevant features that change between display and test in each memory condition. Experiment 4 also included a new set of colour and shape stimuli. These were introduced to minimise the possibility of participants verbalising the stimuli by using abstract shape stimuli (Chuah et al., 2004) and difficult to name colours (Parra et al., 2009). The results of Experiment 4 mirrored those from Experiments 2 and 3 in suggesting that while cognitive load had a negative impact on performance overall, there was no specific detriment to the binding conditions suggesting that both types of binding proceed relatively automatically. Finally, in Experiment 5 we revisited the *ageing-context hypothesis* by administering the task adaptation from Experiment 4 to older and younger adult groups (who completed the concurrent articulation condition only – there was no load manipulation). As in Experiment 1, older adults exhibited generally poorer performance than younger adults for all single feature and bound feature-combination conditions, showing no particular evidence of difficulty in their binding ability. In sum, Experiments 1 and 5 fail to support the *ageing-context hypothesis* because both experiments show only a general decline in performance as a function of age, rather than the predicted specific decline in location binding ability. Furthermore, Experiments 2 and 4 cannot support nor discount the ageing-attention hypothesis to the extent that we have found no evidence to suggest that binding is attentionally demanding (to reiterate, the ageing attention hypothesis would predict that older adults would be impaired on any binding task that was especially attentionally demanding).

2.7.1 Feature Binding and Ageing

Our findings in Experiments 1 and 5 replicate those of Brown and Brockmole (2010) in suggesting that surface-feature binding is not specifically impaired with normal ageing. Our data take this further, however, by also demonstrating that location binding appears to be unaffected too. If an age-related deficit was to be observed, this is where we would have expected to observe it. This finding was somewhat surprising as several studies (e.g. Cowan et al., 2006) have shown evidence that older adults exhibit specific difficulties in remembering objects in their locations. For example, Mitchell et al. (2000) tested younger and older adults on their memory for objects, locations, and combinations of objects and locations. Although their use of serial presentation makes any direct comparison somewhat difficult, Mitchell et al. (2000) showed a specific difference in the false alarm rate of participants, with older adults producing a greater proportion of false alarms in the location binding condition, relative to hits, when compared with their younger adult counterparts. The additional memory requirements of serial presentation offer perhaps the best explanation for the difference in findings between Mitchell et al. (2000) and the experiments reported here.

Returning to our hypotheses that sought to examine older adults' performance, the *ageing-context* hypothesis predicted that older adults should be specifically impaired in our location binding tasks (colour-location; shape-location) on the basis that these were the only conditions to require binding objects to their context (location in space). On the basis of the experiments reported in this chapter, this hypothesis can be rejected. This is interesting not simply due to previous studies reporting location binding deficits (e.g. Cowan et al., 2006; Kessels et al., 2007; Mitchell et al., 2000), but also as older adults are typically reported to be impaired in tasks requiring explicit memory and recall (that is tasks where participants are directed as to what they must remember; Light & Singh, 1987).

Interestingly, the pattern of general decline observed here contrasts with the findings of Meulenbroek et al. (2010) who showed that older adults do not use contextual information to aid recall of object location pairings. The paradigm used in this chapter is not directly comparable to Meulenbroek et al.'s (2010) paradigm but perhaps the simplistic nature of the present task, requiring memory for just three simple objects, meant that declarative memory was sufficient to effectively complete the task, essentially masking differences in how older and younger adults complete the task. Adding weight to this suggestion, Kessels et al.'s (2007) finding of poorer performance in older adults on location binding may have been down to having more complex arrays. Here, seven objects were shown on each trial with a greater number of possible locations than the paradigm used in this chapter. This more complex array elicited specifically poorer performance in older adults, compared to younger adults. In sum, although the experiments in this chapter cast doubt on the *ageing-context hypothesis*, it may actually indicate that the paradigm we have adopted lacks the complexity required to prevent the use of alternative methods to effectively complete the location binding task, thus masking any deficits in the use of contextual information by older adults. As such, one method of more effectively exploring the *ageing-context hypothesis* may be the study of incidental feature binding.

The *ageing-attention* hypothesis, in contrast, suggested that older adults should be impaired on any binding task that is effortful, which, given past research, we would predict to be most likely in location binding conditions (e.g., Elsley & Parmentier 2009; Cowan et al., 2006). Given that Experiments 2-4 failed to find any detrimental impact of cognitive load on either surface-feature binding or location binding, and that Experiments 1 and 5 found a general decline in performance in the older adult groups the ageing-attention hypothesis cannot be rejected. With the impact of cognitive load on younger adults producing the same pattern of results observed in older adults, the ageing-attention hypothesis is supported, but not in the manner initially expected. The relative decline in older adults' feature binding and single feature memory, is seemingly explained by an age related decline in attentional resources.

Our findings differ from those reported by Cowan et al. (2006). One possible explanation for this could be the differences in the arrays. In our paradigms, arrays involved three objects, presented simultaneously each in a unique location, followed by a single probe item. In the study of Cowan et al. (2006) the arrays involved the presentation of four objects, followed by an array which again consisted of four objects though this time with one cued item, upon which participants were to base their response (a judgment of whether it was the same or different to the object presented in the array). Under this notion, Cowan et al.'s (2006) findings could instead be explained in terms of the *ageing-context hypothesis* rather than as being due to divided attention because participants were given the full array at test, allowing them access to the original context of the presentation of the target item. An alternative explanation (and one that accepts the ageing-attention hypothesis as an explanation of Cowan et al.,'s (2006) findings) is that the differences between tasks are driven by task demands across paradigms. Under this notion, a paradigm such as that used by Cowan et al. (2006) that assessed surface-feature binding, should show a specific impairment in that condition, in the same manner as the impairment showed in location binding. The next section discusses in depth, the role of attention in the paradigm used in this chapter.

2.7.2 Feature Binding and Attentional Resources

Experiments 2-4 demonstrated no evidence to suggest that either surface feature binding or location binding, as assessed by the adapted Allen et al. (2006) paradigm, are attentionally demanding processes. The apparent automatic nature of surface-feature binding was not, of itself, surprising given the now numerous demonstrations that this type of binding is immune to cognitive load (e.g. Allen et al., 2006). Although Brown and Brockmole (2010) did report an effect of cognitive load on surface feature binding in a paradigm of this type, it is explained by Allen et al. (2012) as being due to Brown and Brockmole's (2010) use of the A' signal detection measure rather than the more standard *d'*, that is argued to have overestimated the size of the interaction. The repeated demonstrations here that surface feature binding is generally no more resource demanding than remembering the most difficult constituent feature, is consistent with Allen et al. (2006) and lends credence to Allen et al.'s (2012) explanation of Brown and Brockmole's (2010) findings.

The finding that location binding was not attentionally demanding was, however, more surprising, and contrasts with recent findings. Firstly, Hyun, Woodman, and Luck (2009) investigated the role of attention in binding surface features to locations, and found evidence to suggest that location binding was attentionally demanding over and above the attention required for single feature memory. The study used a simple change detection task and recorded the EEG component N2pc as a measure of the allocation of attention (a commonly used EEG measure in attention research; e.g. Eimer, 1996; Kiss, Van Velzen, & Eimer, 2008; Luck, 2012). Location binding conditions (of which there were two; one requiring memory of the exact position of the coloured square termed fine location, and one requiring participants to report in which quadrant the coloured square appeared termed *coarse location*) were shown to elicit a larger N2pc component than conditions where only surface feature memory was required. Additionally, their behavioural findings showed similar effects in terms of reaction times, with binding conditions showing longer reaction times than the single feature condition. Although accuracy was at ceiling in the feature memory condition, and the location binding condition, N2pc was shown to be higher in the binding condition than the feature memory condition. Yet, in three experiments here, no such effect was shown. Although both Hyun et al. (2009) and the adapted Allen et al. (2006) paradigm used in the present set of experiments both explicitly instruct participants to remember feature bindings, there are still differences that may perhaps explain the disparate findings. The paradigm used in Chapter 2 required participants to remember just three coloured objects; in contrast Hyun et al. (2009) presented participants with arrays of 24 squares, some of which were coloured. Perhaps then, the disparate findings are driven by the contextual differences between the paradigms. The greater density of contextual information in Hyun et al.'s (2009) paradigm may require a greater degree of attention to bind objects to locations than the relatively sparse array in the adapted Allen et al. (2006) paradigm. Although findings were not at ceiling here, it is also possible that a greater degree of attention was still required, but that the additional cognitive load was not taxing enough to elicit specific behavioural differences.

Experiment 4 arrays always consisted of coloured shapes in locations, so perhaps these bound combinations were committed to memory in all conditions and thus attention was applied equally throughout the conditions. Indeed, a number of experiments report the incidental binding of objects to locations (Campo et al., 2010; Elsley & Parmentier, 2009; 2015) and Ecker et al. (2013) even suggest similar with intrinsic surface features. Under this explanation, feature salience would then dictate the difference in recall difficulty in the single feature conditions and feature combination conditions when presented with the probe item. This explanation arguably falls in line with the findings of Morey and Bieler (2013) who showed that memory for even very basic arrays is adversely affected by additional cognitive load. Moreover, this is apparent irrespective of whether participants are asked to focus on single features, or bound combinations of features. This tentatively suggests that under instruction to remember single features, or to remember feature bindings, domain general attentional resources are deployed; and according to Experiments 2-4 in this chapter, are seemingly deployed relatively evenly.

The findings reported in Experiments 2-4 also provide a stark contrast to the findings of Elsley and Parmentier (2009) who demonstrated that location binding could be reduced by the addition of a concurrent attentionally demanding task. Aside from the fact that Elsley and Parmentier (2009) used verbal-spatial stimuli (which may in itself drive differences in attentional requirement), one key difference between the paradigm used in this chapter and Elsley and Parmentier (2009) was the need to explicitly commit bindings to memory. While the experiments in this chapter instructed participants to remember specific bindings between features in the combinations task types, Elsley and Parmentier (2009) instructed participants only to remember the letters and locations shown in each array and to judge a single probe letter in location in terms of whether the features were present in the array irrespective of their initial pairing. It must be noted however, that from this paradigm it cannot be ascertained whether the feature bindings emerged incidentally, or as a result of an explicit strategy adopted by participants (who may have bound features intentionally in order to decrease the memory demand of each array).

2.7.3 Summary

In sum, perhaps the consistent lack of interactions between memory condition and both age group and cognitive load condition shown in Chapter 2, in terms of both ageing and attentional load, could be attributed to the paradigm used to assess binding. This adaptation of the paradigm first used by Allen et al. (2006) is a task that explicitly required the committal of bindings to memory – task instructions at the start of each block gave explicit direction as to which feature or combination of features would be task relevant for the coming trials. There are questions to be raised regarding these explicit binding instructions in respect of the manner in which attention is directed. Treisman (2006) suggests that whether our attention is focused or distributed influences the nature of the information processed (a claim analogous respectively to the *focused-attention phase* and *pre-attentive phase* of FIT), and, with binding processes occurring in light of focused attention. Although what is being discussed here perhaps constitutes variations in focused attention, rather than the difference between that and distributed attention, perhaps it can be argued that the instructions in Allen et al.'s (2006) paradigm widen the focus of attention to actively include the relationships between features that would not ordinarily be subject to conscious awareness, or at least not subject to such explicit focus. Hence a question remains over whether such relationships between features would be processed in the same manner as in the Allen et al. (2006) paradigm, under conditions where attention is focused keenly on a single element or feature.

Partially addressing this question, there is some evidence to suggest that, in contrast to younger adults, older adults seemingly do not use contextual information as a cue for object memory. As noted earlier, Chee et al. (2006) showed that under instructions to remember object identity, older adults show the same pattern of brain activation whether the object is presented on a blank screen or on a landscape background picture, suggesting that older adults are not processing the contextual information when not explicitly instructed to do so. The differential activity of younger adults between these two conditions is suggestive of this age group processing the background picture in addition to the task relevant object. Thus, older adults seem to differ to younger adults in the processing of non-task relevant information, offering a clear contrast to the experiments reported here where there is no difference in the pattern of performance for explicitly task relevant information. This, in combination with consistent demonstrations that older adults fail to link incidentally processed information with intentionally processed information (e.g. Naveh-Benjamin et al., 2009; discussed further in the next chapter) suggests that perhaps older adults may fail to use location information in the same way as younger adults, a difference which should present itself under circumstances where bindings are assessed implicitly. This issue forms the basis of Chapter 3.

Chapter Three. Incidental Binding - Ageing and Attention

3. Incidental Binding - Ageing and Attention

3.1 Introduction

Chapter 2 yielded two important findings. First, it demonstrated that older adults maintain the ability to bind visual features (colour, shape) to produce objects, and to bind visual features to locations, showing no impairment relative to younger adults on either type of binding task. This finding was consistent with previous work demonstrating no age-related deficit in the binding of colour s and shapes (Brown & Brockmole, 2008) but further provided a first assessment of location binding ability in older adults using adaptations of the paradigm developed by Allen et al. (2006). Second, our data suggest that neither surface-feature binding nor location binding draw more heavily on attentional resources than memory for single features (as assessed in younger adults). On the basis of these findings, it may appear that feature binding performance (at least between colours and shapes; and colours/shapes and locations) is not subject to decline with advancing age, nor does it require particular cognitive effort. However, the experiments conducted thus far only encompass performance under conditions where participants are explicitly instructed to remember the bindings between features. That is, the binding is intentional insofar as it is specifically instructed in order to complete the task, leaving open the question of whether younger and older adult performance may diverge where bindings between features are not explicitly required for task completion. Here, we chose to focus on the binding of objects to locations as there is some evidence to suggest location binding performance may be specifically impaired in ageing (e.g. Cowan et al., 2006). Beyond this, though, there is reason to suspect that incidental binding performance may be particularly impaired in older adults (see Kensinger, Piguet, Krendl & Corkin, 2005; & Naveh-Benjamin et al., 2009), particularly with regard to binding object to context (with spatial location acting as a contextual cue: Meulenbroek et al., 2010). These issues are discussed in detail below following a review of literature pertaining to incidental binding in younger adults, and the so-called binding asymmetry.

Incidental binding and binding (a)symmetry

Tasks that assess the incidental binding of features typically present participants with multi-feature objects, ask them to remember one type of feature (e.g., the object's shape), and assess the impact on memory for that feature of making irrelevant changes in the task-irrelevant feature (e.g., the object's location). If the task-irrelevant change impairs performance in some way it can be inferred that participants encoded the irrelevant feature along with the relevant one. If the task in question further manipulates the relationship between features so that memory is constrained to binding, these types of tasks are informative on the incidental nature of feature binding in memory. Using this type of logic, Campo et al. (2010), in addition to Elsley and Parmentier (2015), have recently demonstrated an asymmetry in incidental feature binding between objects (visually presented letters) and their spatial locations in younger adults. Their paradigm involved the presentation of four letters simultaneously in distinct locations, then, following a delay, the participant would be presented with a probe letter in a location. In accordance with the instructions for the condition participants were undertaking, they were required to identify either: if the letter was present in the preceding array, irrespective of whether the letter had moved locations; or if the location occupied by the probe was occupied in the preceding array, irrespective of whether the letter in that location had changed. Binding was assessed by comparing performance in response to 'intact' probes (where the probe represented a letter in the same location that it occupied in the array) and 'recombined' probes (where the probe consisted of a letter that was present, occupying a location that previously contained a different letter; i.e. both features were in the array but not in this combination –a pairing of letter and location swapped). Thus, if participants bind incidentally in this task, there should be a performance advantage in the intact condition (bindings preserved) relative to the recombined condition (bindings switched) even though one of the features was never relevant for task completion. Campo et al. (2010) and Elsley and Parmentier (2015) both found that when participants were instructed to remember the identity of the letters, incidental binding of letters to locations was evident (higher accuracy and shorter reaction times in the intact condition relative to the recombined condition). However, when participants were instructed to remember the locations, this intact/recombined probe difference was absent, indicating that memory for the locations in the array was not disrupted by changes in letter identity. This suggests that the locations may have been held in memory independently of their contents. Thus, objects (in this case letters) were incidentally bound to their location but locations could be remembered independently of the objects (in this case, letters) within them, a pattern of performance we refer to as a *binding asymmetry*. Facilitation in the intact condition relative to recombined condition is thought to reflect both facilitation where the probe perfectly matches the representation held in memory in addition to a potential 'decomposition cost' incurred when attempting to match the recombined probe features to those present in the memory array (Prabakaran et al., 2000).

Chapter 3 aimed to apply the logic of this task to the study of older adult memory on the basis that there is reason to believe that older adults may be impaired in terms of their ability to incidentally bind features in short term memory. For example, Naveh-Benjamin et al. (2009) showed that older adult memory for face-name pairings, while comparative to younger adults under explicit instructions to remember the combinations, was poorer than younger adults when instructions were just to remember the faces. Furthermore, Kensinger, Piguet, Krendl and Corkin (2005) reported corroborative findings in terms of contextual information and emotion processing. Younger and older participants in this study reviewed images containing an emotionally evocative component which could be negative, positive or neutral, and consisted of a central emotional element with a neutral peripheral element (for example a negative image was a desert landscape with a dead cat in the foreground). Instructions were for the participant to indicate whether they wanted to approach or withdraw from the image. Following this, participants were given an unrelated working memory tasks for 15 minutes and then tested on their memory for details of the images they had been shown. In one experiment, participants were not informed about the final test phase until such time as they were tested (incidental encoding), and in a subsequent experiment participants were informed of the final test phase at the beginning of the experiment (intentional encoding). Intentional encoding allowed younger adults to overcome the attentional bias of negative image elements, whereby peripheral image elements were not encoded under incidental encoding as attention is drawn by the negative elements (in the example earlier, under incidental encoding the dead cat would be encoded but not the desert scene). Older adults showed no such difference, unable to overcome the attentional bias of negative imagery even under intentional encoding instructions, further demonstrating encoding differences between younger and older adults.

More relevant for the current review, Meulenbroek et al. (2010) showed that while younger adults use contextual information from the environment as cues to aid recall of object-location pairings (argued by Meulenbroek et al. to represent the use of mental imagery) older adults do not, relying instead on pure stimulus response associations. Using an episodic memory task, this study investigated object-location pairings in two visual conditions: (1) a rich environmental support condition, where all objects are presented simultaneously; and (2) a poor environmental support condition, where each object was presented sequentially (equating to serial presentation). Younger adults were shown to systematically use the rich environmental support, seeming to mentally place the objects near to one another to aid object recall. Conversely, older adults seem not to use the rich environmental support. The task was subsequently adapted for use with fMRI, where the younger and older adults showed different patterns of brain activation supporting the use of mental imagery by younger adults (posterior brain regions related to mental imagery were recruited by younger adults only), while older adults recruited brain regions associated with declarative memory (basal ganglia, thalamus, left middle temporal/fusiform gyrus and right medial temporal lobe). Thus the older adults seemed to be reliant on stimulus-location associations in order to complete the task, unlike younger adults who used mental imagery. This again suggests that older adults are reliant on memory for just the feature or object required to complete a task to the detriment of memory for additional information, implying that older adults would not bind objects to locations unless specifically instructed to do so. Taken together, these studies indicate that older adults may perform differently to their younger counterparts on a paradigm such as that devised by Campo et al. (2010) investigating the symmetry of binding in an incidental binding paradigm. This issue is addressed across three experiments in Chapter 3, the first of which examines verbal-spatial binding (a)symmetry in younger and older adults, discussed in detail below.

3.2 Experiment 6: Binding (a)symmetry and ageing: verbal-spatial features.

Experiment 6 was an adaptation of Campo et al.'s study (2010) assessing the (a)symmetry of verbal-spatial bindings with the addition of age group (younger, older) as a between subjects factor, differing in the use of probe types, with Experiment 6 using all five probe types in both task relevancy conditions (explained in depth in Chapter 3.2.1.4) compared with Campo et al.'s (2010) use of four probe types per task relevancy condition. In each trial, a participant was shown four letters, each in a unique location and presented simultaneously. After a short delay, participants were presented with a single probe letter. There were two memory conditions that differed only in terms of the instructions given: to remember the letter identities, or to remember the locations. The associations between letters and locations were never explicitly task relevant, however the two critical probes were a letter in its original location (intact probes), and a letter in a location previously occupied by a different letter (recombined probes). The comparison of these two probe types allowed the assessment of incidental letter-location binding. For younger adults, this paradigm typically evidences an intact (bindings preserved) over recombined (bindings switched) probe advantage (Campo et al., 2010), but only in the memory condition requiring memory for letters only and not when participants were instructed to remember the locations only, hence, the bindings were asymmetrical to the extent that they did not occur in both attended feature conditions. In our adaptation of this task, we would therefore predict that younger adults would show evidence of binding asymmetry – binding letters to their locations under instructions to remember 'what' the letters are, but not under instructions to remember the pattern of filled locations (Campo et al., 2010).

Given that older adults' (1) may not encode task-irrelevant information incidentally (e.g. Naveh-Benjamin et al., 2009), (2) appear to exhibit a reduced ability to use contextual information in advanced age (Kessels et al., 2007) and (3) may instead rely upon pure stimulus response associations rather than using location as an organisational cue (Meulenbroek et al., 2010), we therefore predict that older adults will not show binding asymmetry, but instead, their performance will be characterized by a lack of difference between intact and recombined conditions across attended feature conditions. Experiment 6 constitutes a re-visitation of the *ageing-context hypothesis*, which, by way of a reminder, suggests that older adults may exhibit a specific deficit in contextual memory (Chee et al., 2006; Meulenbroek et al., 2010). If evidence for the ageing-context hypothesis is gained here, then taken in conjunction with the findings of Chapter 2, this may suggest that older adults do not bind objects to their locations without explicit instructions to do so.

3.2.1 Method

3.2.1.1 Participants

Fifty one participants took part in the 35-minute study. Thirty six were younger adults from the student population of Bournemouth University (25 females, 9 males), aged 19-28 years (M = 21.23, SD = 2.18), with a mean number of years of education of 12.45 (SD = 1.28) and a mean verbal IQ, predicted by the Weschler Test of Adult Reading (WTAR) of 115.32 (SD = 7.01). The older adult group consisted of 15 volunteers (9 females, 6 males), aged 66-73 years (M = 69.34, SD = 4.45), with a mean number of years of education of 11.52 (SD = 2.37) and a mean verbal IQ, predicted by the WTAR of 117.73 (SD = 4.39). There was no difference in predicted verbal IQ scores between the age groups ($t(49) = 1.27$, $p = .15$). The MoCA (Nasrendine et al., 2005) was again administered to the older adults. In accordance with Luis et al. (2009) and the procedures used in Chapter 2, a cut off score of 23 was used (no participants failed to meet this criteria), the mean score was 27.80 (SD = 1.74). In addition, participants reported no significant memory problems and normal or corrected-to-normal vision. All participants received either course credit or an honorarium for participation.

3.2.1.2 Materials

Following Campo et al. (2010) the stimuli were 8 consonants selected for different appearance in upper and lower-case forms (D,F,H,J,N,Q,R,T). Each stimulus was presented in white (Arial font; 48 pt) on a black background and each within a l.87°xl.87° white frame so as to reduce variations in spatial configurations caused by changes in the consonants between array and test (Delvenne et al., 2002). On each trial, the to-be-remembered (TBR) array consisted of four letters (sampled without replacement) that were presented in a circular array of eight possible locations 3.63° each from the screen centre (see Figure 3.1) on a 20" monitor. The probe consisted of a single letter presented in one of the eight possible locations. Responses were collected on a standard keyboard. The task was purpose written for Matlab using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner, Brainard & Pelli, 2007).

3.2.1.3 Design

Experiment 6 took a 2 (age group: younger, older) x 2 (relevant feature: Letters, Locations) x 5 (probe type: intact, recombined, new-letter/location (positive); new-letter/location (negative); both new) mixed design, with age group as a between subjects factor. Accuracy (% correct) and response times (for correct responses only) were the dependent measures.

3.2.1.4 Procedure

Before starting the binding task, participants completed the WTAR to gain an estimate of Verbal IQ. Older Adults also completed the MoCA as a measure of cognitive functioning. The paradigm used in Experiment 6 closely replicated the procedures of Campo et al. (2010) with the exception that the fixed response window of 1000ms was removed due to the expected longer response latencies of the older adults. Each participant took part in two memory tasks, each with different instructions (although what was presented to them was the same in each task). Given arrays consisting of four consonants presented in distinct locations, in the verbal task they were instructed to remember only the letters present in the array (while the locations are task irrelevant); while in the spatial task they were asked to remember the locations that were filled in the memory array, while the identity of the letters was task irrelevant. Each task began with self-paced set of instructions and examples presented on screen. Older participants also received these instructions verbally to ensure that the task was understood. In each of the tasks (attend-verbal and attend-spatial), each trial began with the 1000ms presentation of a two digit number that participants were instructed to ignore (they were not relevant for the purposes of this study, but retained to keep procedures equivalent between Experiments 6 and 7). Participants were then presented with a central fixation cross (500ms) followed by the presentation of the TBR array of four consonants (sampled without replacement) each in a randomly selected location which remained on screen for 2000ms. At the end of this period a pattern mask (50ms) and delay (1150ms) preceded the presentation of a single lower case letter in a location (the probe) to which participants had to respond 'yes' if the item was in the array or 'no' if the item was not in the array by pressing the 'f' or 'j' key on a keyboard. The nature of this decision depended on the task they were undertaking. In the verbal task, they were to respond as to whether the probe represented a letter that was present in the array, regardless of whether it had moved locations; while in the spatial task they were asked to respond as to whether the probe represented a location that was filled in the memory array, regardless of whether the letter filling the location had changed. In each memory condition (verbal; spatial), trial presentation was identical, both visually and in terms of procedure. The order of completion of each task was counterbalanced across participants.

There were five probe types (the correct response to which varied depending on task instructions): (1) a displayed letter in its original location (intact probe); (2) a displayed letter in a location previously occupied by a different letter (recombined probe); (3) a displayed letter in a previously unoccupied location (new location probe); (4) a non-displayed letter in a previously occupied location (new letter probe); and (5) a non-displayed letter in a new location (new both probe). The verbal task required a 'yes' response to intact probes, recombined probes, and new location probes as each of these probe variations contained a letter that had been seen in the TBR array. New-letter and new-both probes were each correctly responded to with a 'no' response.

The spatial task required a 'yes' response to intact probes, recombined probes, and new letter probes (as each featured a seen-before location), and a 'no' response to the new location and new both probes (see Figure 3.1 for trial procedure and probe types)[3]. The ratio of yes to no responses was 1:1. In the letter condition there were 8 trials each of the intact, recombined, and new location probes, and 12 trials each of the new letter and new both probes. In the location condition, there were 8 trials each of the intact, recombined, and new letter probes, and 12 trials each of the new location and new both probes. In both tasks, in line with Campo et al.'s (2010) task instructions, participants were instructed to respond as quickly yet as accurately as possible. Each task featured 12 practice trials followed by two blocks of 48 experimental trials, with trial type (intact, recombined, new-letter, new-location, new-both) randomised within each block.

[3] Note that Campo et al. (2010) used only four probe types per task, two probe types requiring a positive response, and two requiring a negative response. Their letters task used Intact and Recombined positive probes; and New Letter and New Both negative probes. Their spatial task again used Intact and Recombined positive probes; but New Location and New Both negative probes

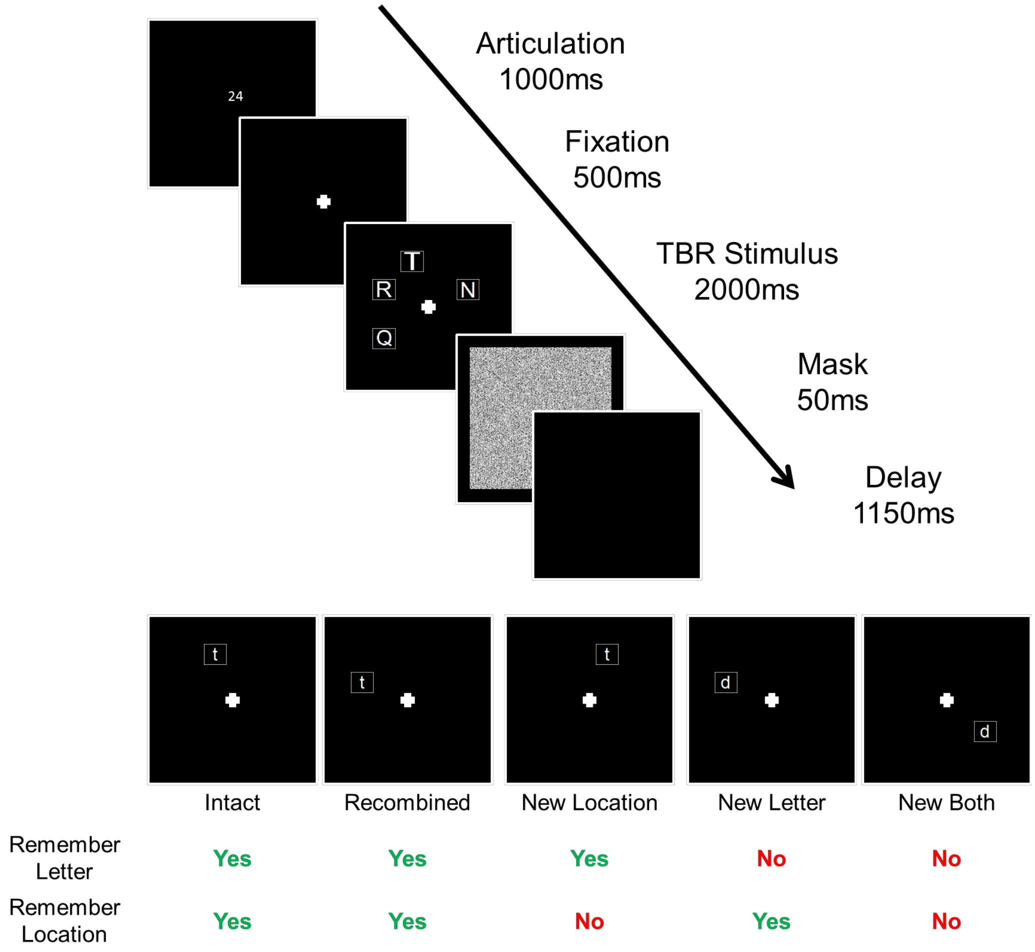


Figure 3.1. Trial procedure and example probes in Experiment 6, with correct responses for each condition. Note that the letters differed between array and test in terms of their visual form (upper versus lower case, respectively) in order to prevent a visual memory strategy.

3.2.1.5 Data Analysis

The measure of binding in this task is based upon comparison of two critical probe types: Intact probes and recombined probes. Thus, the analyses presented below focus on these two probe types as a function of attended feature (letters; locations) and age group (younger, older) in terms of accuracy (% correct) and response times (for correct responses only)[4]. For completeness, an analysis of all three positive probe types, in addition to the two negative probe types are presented in Appendix A. Following the omnibus analyses on each dependent measure, independent analyses of the younger adults and older adults were conducted based on our a-priori hypotheses regarding performance in each age group (as the hypotheses predict null differences in three of the four key comparisons, the likelihood of a type II error in the key triple interaction between age group, relevant feature, and probe type was relatively high). These additional analyses may reveal an otherwise masked effect.

A bayesian ANOVA was also conducted to complement each traditional ANOVA with all models considered equally likely due to the introduction of older adult participants which makes the impact of the Age Group variable on the models impossible to predict. T-tests were also supplemented with their bayesian equivalents. All analyses were again conducted using JASP statistical software (JASP Team, 2016).

[4] Analysis focused on accuracy and reaction times rather than the d' measures used in Chapter 2. This was to allow for a direct comparison to existing published data (Campo et al., 2010, Elsley & Parmentier, 2015 which all used pure accuracy measures and reaction times rather than the response sensitivity favoured by Allen et al, 2006, Brown & Brockmole, 2010 etc.). In addition, the nature of this experiment did not allow for the simple calculation of d' as the 'hit' and 'false alarm' response here constitute separate levels of the probe type condition rather than existing as part of the same condition as in Chapter 2.

3.2.2 Results

Binding (a)symmetry as a function of age: Verbal-spatial features

Accuracy: A 2 (age group: younger, older) x 2 (relevant feature: letter, location) x 2 (probe type: intact, recombined) mixed effects ANOVA with age group as a between subjects factor showed no significant main effect of age group, F (1,49) = 1.99, MSE = 304.20, p = .16, ηp^2 = .0.04, BF_{10} = 0.39; a significant main effect of probe type, F (1,49) = 5.57, MSE = 651.60, p = .02, ηp^2 = .10, BF_{10} = 2.96, with performance in the intact probe condition (M = 93.95 SD = 5.77) better than that in the recombined probe condition (M = 89.97, SD = 10.09); and a significant main effect of relevant feature, F (1,49) = 9.85, MSE = 1746.36, p = .003, ηp^2 = .17, BF_{10} = 259.92, whereby fewer errors were committed in letters condition (M = 95.05, SD = 5.15) than in the locations condition (M = 88.87, SD = 11.75). In terms of interactions, that between relevant feature and age group was non-significant, F (1,49) = 0.03, MSE = 4.66, p = .87, ηp^2 = .001, BF_{10} = 0.26, similarly so for the probe type by age group interaction, F (1,49) = 0.05, MSE = 5.24, p = .83, ηp^2 = .001, BF_{10} = 0.23, and the relevant feature by probe type interaction, F (1,49) = 0.14, MSE = 11.96, p = .71, ηp^2 = . 003, BF_{10} = 0.22. The three-way interaction was also non-significant, F (1,49) = 0.03, MSE = 2.82, p = .86, ηp^2 = .001, BF_{10} = 0.29. In sum, the accuracy analysis provided evidence for superior performance in the letters condition compared to the locations condition, in addition to evidence for binding but this effect was not modified by either attended feature or age group. Data are presented in Figure 3.2.

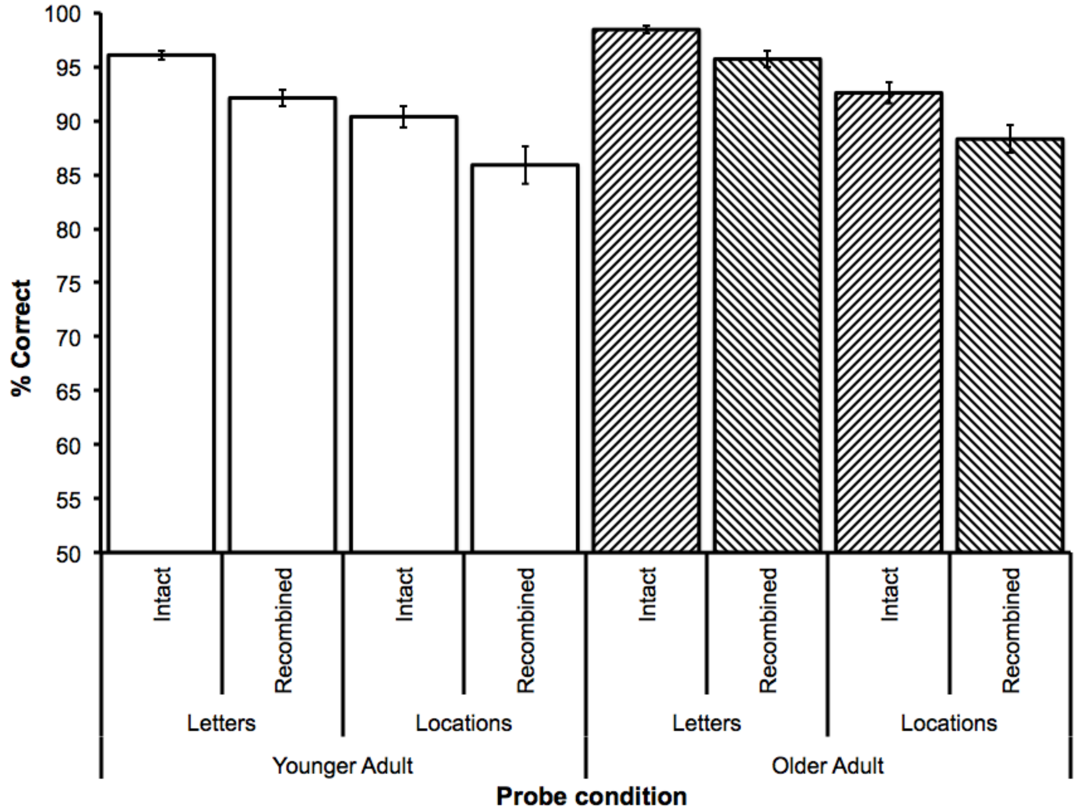


Figure 3.2. Younger and older adult mean accuracy for positive response probe types (intact and recombined) in each relevant feature condition (letter and location) as a function of age. Bars represent one standard error of the mean.

Reaction Time: A similar repeated measures ANOVA conducted on reaction time measures indicated a significant main effect of age, F (1,49) = 22.73, MSE = 8.25^{e+7}, p < .001, ηp^2 = .32, BF_{10} = 999.59, with older adults (M = 1439ms, SD = 337ms) slower than younger adults (M = 1006ms, SD = 377ms); a significant main effect of probe type, F (1,49) = 5.88, MSE = 189966, p = .02, ηp^2 < .11, BF_{10} = 0.71, whereby responses to intact probes (M = 1111ms, SD = 387ms) were quicker that those to recombined probes (M = 1173ms, SD = 444ms) though note the insensitive Bayes factor; and a significant main effect of relevant feature, F (1,49) = 11.57, MSE = 1.14^{e+7}, p = .001, ηp^2 = .19, BF_{10} = 156.27, where responses in the letter condition (M = 1077ms, SD = 287ms) were quicker than responses in the locations condition (M = 1206ms, SD = 508ms). There was no significant interaction between probe type and age group, F (1,49) = 0.13, MSE = 4189, ηp^2 = .003, BF_{10} = 0.23; between relevant feature and probe type, F(1,49) = 0.71, MSE = 18848, p = .41, ηp^2 = .01, BF_{10} = 0.23, though the relevant feature and age group interaction was non-significant, F (1,49) = 3.43, MSE = 339339 , p = .07, ηp^2 = .07, BF_{10} = 3.28, with Bayes Factors supporting the interaction over the null. The three way interaction was non-significant, F (1,49) = 0.25, MSE = 6662, ηp^2 = .005, BF_{10} = 0.23.

Subsequent tests indicated that older adults showed no difference between intact (M = 1401ms, SD = 270ms) and recombined probe performance (M = 1477ms, SD = 275ms), t (15) = 1.65, p = .12, d = .41, BF_{10} = 0.78, while younger adults similarly demonstrated no significant binding effect between intact probes (M = 978ms, SD = 286ms) and recombined probes (M = 1034ms, SD = 371ms), t (34) = 1.86, p = .07, d = .31, BF_{10} = 0.84). Thus, neither older adults nor younger adults show evidence of binding between letters and locations. The data are presented in figure 3.3

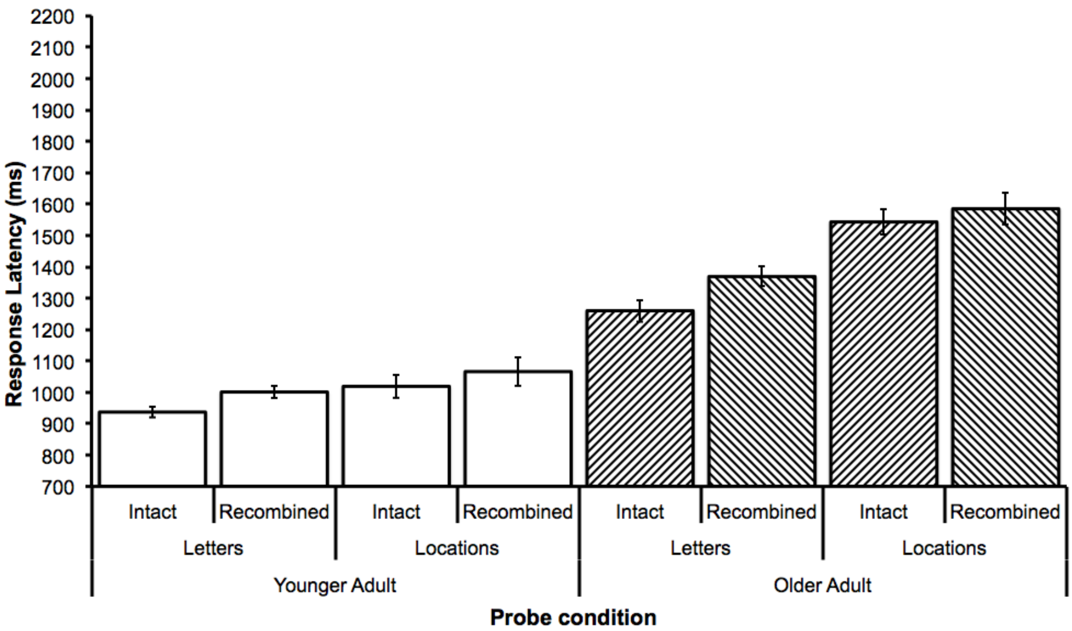


Figure 3.3. Younger and older adult mean reaction time for positive response probe types (intact and recombined) in each relevant feature condition (letter and location) as a function of age. Bars represent one standard error of the mean.

In sum, the omnibus analysis on response times indicated no evidence for binding in either older or younger adults. Given that the omnibus analysis suggests Experiment 6 failed to replicate Campo et al.'s (2010) binding asymmetry in younger adults, analyses based on our a priori hypotheses were conducted on each age group independently. These are presented below, beginning with younger adults.

Binding (a)symmetry in younger adults: Verbal-spatial features

Accuracy: A 2 (relevant feature: letter, location) x 2 (probe type: intact, recombined) repeated measures ANOVA indicated a significant main effect of probe type, F (1,34) = 3.98, MSE = 616.56, p = .05, ηp^2 = .11, BF_{10}

= 1.03, with better performance in the intact probe condition (*M* = 93.24, *SD* = 6.23) relative to the recombined probe condition (*M* = 89.04, *SD* = 11.28; though the insensitive Bayes factor casts doubt on this difference); and a significant main effect of relevant feature, *F* (1,34) = 5.55, *MSE* = 1251.61, *p* = .02, ηp^2 = .14, BF_{10} = 7.21, whereby fewer errors were committed in letters condition (*M* = 94.13, *SD* = 5.60) than in the locations condition (*M* = 88.15, *SD* = 13.04). The relevant feature by probe type interaction was not significant, *F* (1,34) = 0.02, *MSE* = 2.53, *p* = .89, ηp^2 = .001, BF_{10} = 0.25.

Reaction Time: An ANOVA as above conducted on reaction time data showed no main effect of probe type, *F* (1,34) = 3.44, *MSE* = 109760, *p* = .07, ηp^2 = .09, BF_{10} = 0.43 (Intact: *M* = 978.00, *SD* = ; Recombined: *M* = 1033.50, *SD* =) , with the Bayes factor tending toward support for the null; no main effect of relevant feature, *F* (1,34) = 1.66, *MSE* = 189005, *p* = .21, ηp^2 = .05, BF_{10} = 0.87; and no interaction between relevant feature by probe type, *F*(1,34) = 0.12, *MSE* = 2470, *p* = .73, ηp^2 = .004, BF_{10} = 0.26.

In sum, we predicted that, in line with past studies using this method (Campo et al. 2010; Elsley & Parmentier, 2015), younger adults should exhibit binding asymmetry. That is, evidence for binding when letters are task relevant, but no evidence for binding when locations are task relevant. Instead, the analyses reported here suggests evidence for binding in each attended feature condition (c.f. the Bayes factors). The reason for this discrepant finding will be discussed below following an analysis of older adult performance.

Binding (a)symmetry in older adults: Verbal-spatial features

Accuracy: A similar repeated measures ANOVA, conducted on accuracy measures showed a significant main effect of probe type, F (1,15) = 6.34, MSE = 196.70, p = .02, ηp^2 = .30, BF_{10} = 1.41, with performance in the intact probe condition (M = 95.52, SD = 4.41) better than that in the recombined probe condition (M = 92.02, SD = 6.65) though again the Bayes factor is insensitive in this comparison; and a significant main effect of relevant feature, F (1,15) = 10.43, MSE = 703.58, p = .006, ηp^2 = .41, BF_{10} = 253.16, whereby accuracy was higher in the letters condition (M = 97.08, SD = 3.31) than in the locations condition (M = 94.16, SD = 4.55). The relevant feature by probe type interaction was not significant, F (1,15) = 0.65, MSE = 9.61, p = .43, ηp^2 = .04, BF_{10} = 0.37. Figure 3.3 shows the accuracy for younger and older adults in each condition.

Reaction Time: An ANOVA as above on reaction time showed no main effect of probe type, F(1,15) = 0.61, MSE = 1.64^{e+7}, p = .45, ηp^2 = .04, BF_{10} = 0.35; or of relevant feature, (F(1,15) = 0.14, MSE = 341933, p = .71, ηp^2 = .009, BF_{10} = 0.38); or any evidence for an interaction between these factors (F(1,15) = 0.87, MSE = 2.10^{e+7}, p = .37, ηp^2 = .06, BF_{10} = 0.36).

3.2.3 Discussion

Experiment 6 investigated the effects of ageing on incidental binding ability (e.g., the binding that takes place between features regardless of task instructions, in this case, letters and locations). In particular, following a recent demonstration of binding asymmetry (the observation that letters bind to their locations when letters are task relevant, but that locations do not bind to letters when locations are task relevant: Campo et al. 2010; see also Elsley & Parmentier, 2015), and, in addition to evidence suggesting older adults may be impaired at the incidental binding of objects to their context (Chee et al., 2006), Experiment 6 investigated whether older adults would exhibit the same pattern of asymmetry as younger adults. Through the presentation of arrays consisting of four consonants presented in distinct locations, and varying task instructions (to remember the letters in the array while locations were task irrelevant; or to remember the locations in the array while the letters were task irrelevant); we predicted firstly that younger adults would exhibit evidence of binding letters to locations when instructed to remember letter identity, but no such evidence when instructed to remember locations. In contrast, older adults were predicted to show no such asymmetry, with no evidence of object to location binding under either set of instructions (Chee et al., 2006). The accuracy data failed to support either hypothesis. Younger adults did not show the predicted binding asymmetry, and both groups of participants showed evidence of a binding effect (intact over recombined probe advantage) consistent with the binding of verbal and spatial feature in both attended feature conditions. Thus, regardless of attended feature or age, incidental binding between verbal and spatial features occurred. In respect of reaction time measures, no consistent effect of either probe type or relevant feature was shown in either age group, again standing contrary to the hypothesis.

It would seem then that both younger and older adults demonstrate incidental binding of letters and locations irrespective of the attended feature. Aside from the lack of replication of previous results in respect of younger adults (discussed further below), this lack of a difference in binding performance between younger and older adults is somewhat surprising. Previous evidence suggests that older adults should not incidentally bind objects and locations. Both Chee et al. (2006) and Meulenbroek et al. (2010) indicated that older adults fail to use contextual information in the same manner as younger adults. The data here suggest that such contextual information (location in the case of this experiment) is being used to aid memory recall. It must be noted though, that this experiment did not replicate the performance of the study on which it is based (Campo et al., 2010) in respect of younger adult performance. As such, rather than progressing too far in interpreting older adult performance, we may be best served by initially looking at possible explanations for this lack of replication.

Given how closely the procedure and design of Experiment 6 mirrored that of Campo et al. (2010), the lack of evidence for binding asymmetry in the younger adult group is difficult to account for. One potential explanation lies in the methodological differences – firstly that Campo et al. (2010) forced participants to respond within a 1000ms window, while here that response window was removed due to the expected longer reaction times of our older participants. Under this interpretation, the response window may have increased the time pressure resulting in higher task difficulty in Campo et al.'s (2010) task version than was present here (which would also explain why performance in Experiment 6 was at ceiling while performance in Campo et al.'s task was not). This interpretation is unlikely, however, as Elsley and Parmentier (2015) demonstrated binding asymmetry without a response window. The second difference lies in the use of five probe types in Experiment 6, compared to Campo et al.'s (2010) use of four probe types per task. However, with analysis focused on two positive probe types only (Intact and Recombined) it is again difficult to ascertain how this would impact performance in such a way as to not produce the previously shown asymmetry. Nevertheless, it is clear that performance in Experiment 6 did approach ceiling, which may have masked any potential differences in probe performance across our conditions. One potential way to avoid this in future experiments may be to include a variable response window based on the reaction times of individual participants. Alternatively, the difficulty of the TBR array objects could be increased. This latter approach was taken in Experiment 7, where we introduced the abstract shapes used in Chapter 2, additionally allowing a direct assessment of visuo-spatial binding and aligning Experiment 7 with previous experiments in this thesis. Thus, Experiment 7 constituted a direct replication of Experiment 6 only using hard to name irregular polygons instead of consonants as TBR stimuli.

3.3 Experiment 7: Binding (a)symmetry and ageing: visual-spatial features.

Experiment 7 replicated the paradigm and procedure used in Experiment 6, but introduced visual stimuli in place of verbal stimuli. Shapes of the type used in Experiments 4 and 5 (devoid of colour, in a white outline) were introduced to both draw performance away from ceiling, and make the findings of this experiment more directly comparable to those in Chapter 2. The move to visual-spatial features also meant the reintroduction of concurrent articulation in an attempt to restrict verbal re-coding/rehearsal. Concurrent articulation is expected to have a minor impact on task difficulty, further reducing the likelihood of replicating the ceiling effect observed in Experiment 6 (see also Allen et al., 2006; Brown and Brockmole, 2010, where concurrent articulation was used as a low memory load condition). The hypotheses remained the same as those presented in Experiment 6: first, we predict younger adults should produce performance consistent with binding asymmetry (binding in the attend-shapes task but not the attend-locations task). Predictions with regard to older adults are more difficult to present. While past literature would suggest older adults will show no difference between probe types in either relevant feature condition on the basis that ageing impairs incidental binding ability (Chee et al., 2006; Meulenbroek et al., 2010), the results of Experiment 6 would seem to suggest that older adults bind regardless of attended feature.

3.3.1 Method

3.3.1.1 Participants

Fifty six participants took part in the 35 minute study. Thirty five were younger adults from the student population of Bournemouth University (31 females, 4 males), aged 18-27 years (*M* = 20.39, *SD* = 2.68), with a mean number of years of education of 13.56 (*SD* = 1.29) and a mean verbal IQ, predicted by the Weschler Test of Adult Reading (WTAR) of 113.39 (*SD* = 6.35). The older adult group consisted of 21 volunteers (13 females, 8 males), aged 65-82 years (*M* = 71.35, *SD* = 5.35), with a mean number of years of education of 14.58 (*SD* = 2.58) and a mean verbal IQ, predicted by the WTAR of 120.42 (*SD* = 4.67). Predicted verbal IQ was higher in older than in younger adults, t (55) = 3.67, $p < .001$. Older adults were screened for unhealthy cognitive decline using the MoCA (Nasrendine et al., 2005; *M* = 27.58, *SD* = 1.68) with no participants achieving a score lower than the cutoff score of 23 (Luis et al., 2009). As before, no participants reported significant memory problems and all had normal or corrected-to-normal vision. All participants received either course credit or an honorarium for participation.

3.3.1.2 Materials

The stimuli consisted of 8 shapes of the type used in Experiments 4 and 5 (Chapter 2), previously piloted to ensure low nameability (Chuah et al., 2004). Each stimulus was presented in white outline on a black background and each within a l.87° x l.87° white frame so as to reduce variations in spatial configurations between the shapes (Delvenne et al., 2002). On each trial, TBR array consisted of four stimuli (shapes sampled without replacement) presented in a circular array of eight possible locations each 3.63° from the screen centre, on a 20" monitor. The probe consisted of a single shape presented in one of the eight locations (Figure 3.4). The task was purpose written using Matlab and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007). Responses were collected via standard keyboard.

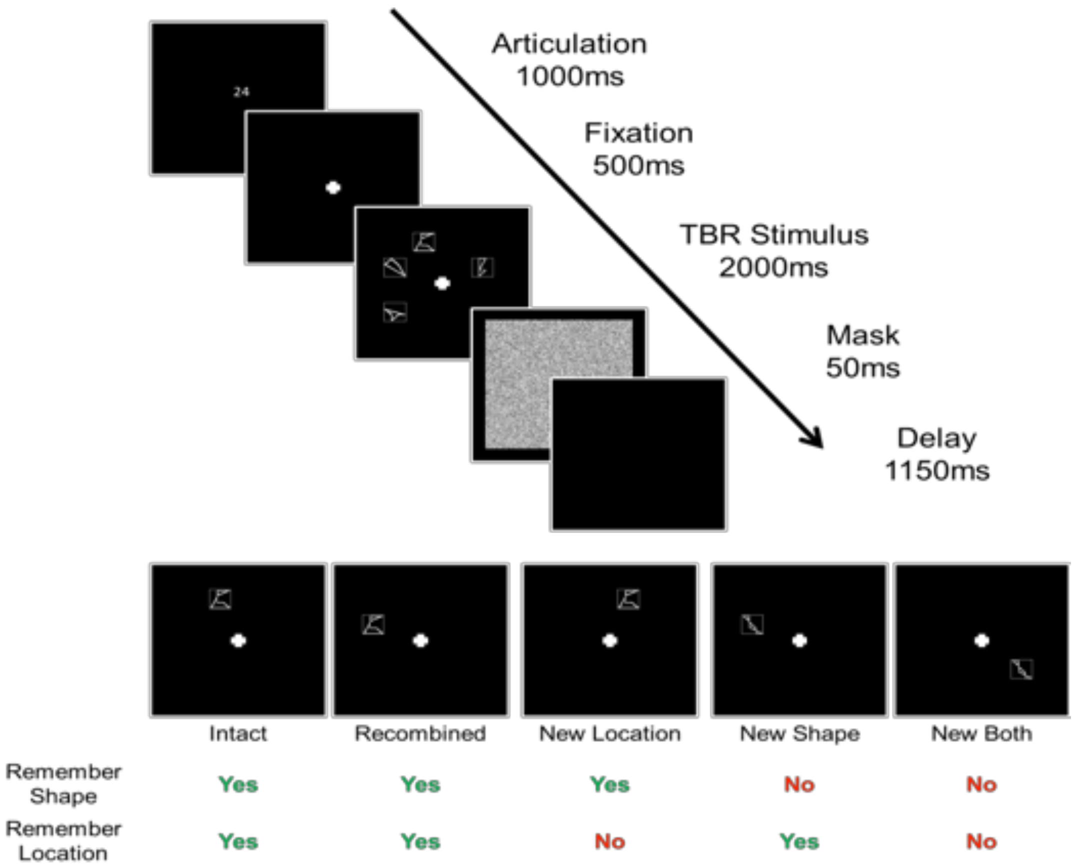


Figure 3.4. Trial procedure and example probes with correct responses for each condition used in Experiment 7.

3.3.1.3 Design

The design of Experiment 7 was as in Experiment 6.

3.3.1.4 Procedure

The procedure used in Experiment 7 was as in Experiment 6 with the following exceptions. Firstly the TBR stimuli changed to shapes (see Materials section for details) rather than letters. Secondly, with the move away from verbal stimuli, concurrent articulation had to be re-introduced in order to limit the verbal-recoding of our visuo-spatial stimuli. To this end, participants were instructed to repeat out loud a number displayed at the start of each trial, from the moment it appeared until a response was made via keyboard.

3.3.1.5 Data Analysis

Data analysis was conducted as in Experiment 6, with the additional analyses on all three positive probes types in addition to negative probes appearing in Appendix B.

3.3.2 Results

Binding (a)symmetry as a function of age: Visuo-spatial features

Accuracy: The repeated measures ANOVA (with age group as a between subjects factor) conducted on accuracy showed no significant main effect of age group, F (1,55) = 1.47, MSE = 510.00, p = .23, ηp^2 = .0.03, BF_{10} = 0.39; a significant main effect of probe type, F (1,55) = 7.66, MSE =

1155.36, p = .008, ηp^2 = .12, BF_{10} = 2.34, with performance in the intact probe condition (M = 79.18, SD = 14.10) better than that in the recombined probe condition (M = 74.89, SD = 16.37), though it must be noted that Bayes factor was insensitive here; and a significant main effect of relevant feature, F (1,55) = 9.37, MSE = 2156.61, p = .003, ηp^2 = .15, BF_{10} = 305.42), whereby fewer errors were committed in location condition (M = 80.53 , SD = 17.39) than in the shapes condition (M = 73.54, SD = 12.20). In terms of interactions, that between relevant feature and age group was non-significant, F (1,55) = 2.05, MSE = 471.48, p = .16, ηp^2 = .04, BF_{10} = 0.72), similarly so for the probe type by age group interaction, F(1,55) = 0.77, MSE = 116.27, p = .38, ηp^2 = .01, BF_{10} = 0.24; although the relevant feature by probe type interaction was significant, F(1,55) = 5.50, MSE = 506.95, p = .02, ηp^2 = .09, BF_{10} = 0.44. The three-way interaction, however, did not reach statistical significance, F(1,55) = 3.35, MSE = 309.06, p = .07, ηp^2 = .06, BF_{10} = 0.55) although the Bayes factor was insensitive, tending toward favour for the null hypothesis (see figure 3.5).

Figure 3.5. Younger and older adult mean accuracy (% correct) for intact and recombined probes as a function of relevant feature. Bars represent one standard error of the mean.

Reaction Time: A similar repeated measures ANOVA conducted on reaction time measures indicated a significant main effect of age, F (1,55) = 53.59, MSE = 3.13^{e+8}, $p < .001$, $\eta p^2 = .49$, $BF_{10} = 8.04^{e+7}$), with older adults (M = 1883ms, SD = 671ms) slower than younger adults (M = 1122ms, SD = 370ms); no main effect of probe type, F (1,55) = 0.05, MSE = 6718, $p = .82$, $\eta p^2 < .01$, $BF_{10} = 0.15$; and no main effect of relevant feature, F (1,55) = 1.02, MSE = 176523, $p = .32$, $\eta p^2 = .02$, $BF_{10} = 0.15$. There was no significant interaction between probe type and age group, F (1,55) = 0.37, MSE = 47869, $\eta p^2 < .01$, $BF_{10} = 0.23$, between relevant feature and probe type, F (1,55) = 0.94, MSE = 136617, $p = .34$, $\eta p^2 = .02$, $BF_{10} = 0.32$, but the relevant feature and age group interaction was significant, F (1,55) = 8.44, MSE = 1.46^{e+7}, $p < .01$, $\eta p^2 = .13$, $BF_{10} = 16.12$).

Further tests decomposing the interaction between relevant feature and age group indicated no difference in response times between the shapes task (*M* = 1772ms, *SD* = 451ms) and the locations task (*M* = 1994ms, *SD* = 655ms) for older adults, t (21) = 1.78, p = .09, d = .38, BF_{10} = 0.86), while younger adults were slower in the shape condition (*M* = 1176ms, *SD* = 365ms) relative to the location condition (*M* = 1069ms, *SD* = 302ms; t(34) = 2.39, p = .02, d = .41, BF_{10} = 2.17). The three way interaction was non-significant, F (1,55) < 0.01, BF_{10} = 0.29: see Figure 3.6). Given our a priori hypotheses regarding (particularly) younger adult performance on this task, separate analyses were conducted on younger and older adults, respectively. These are presented below.

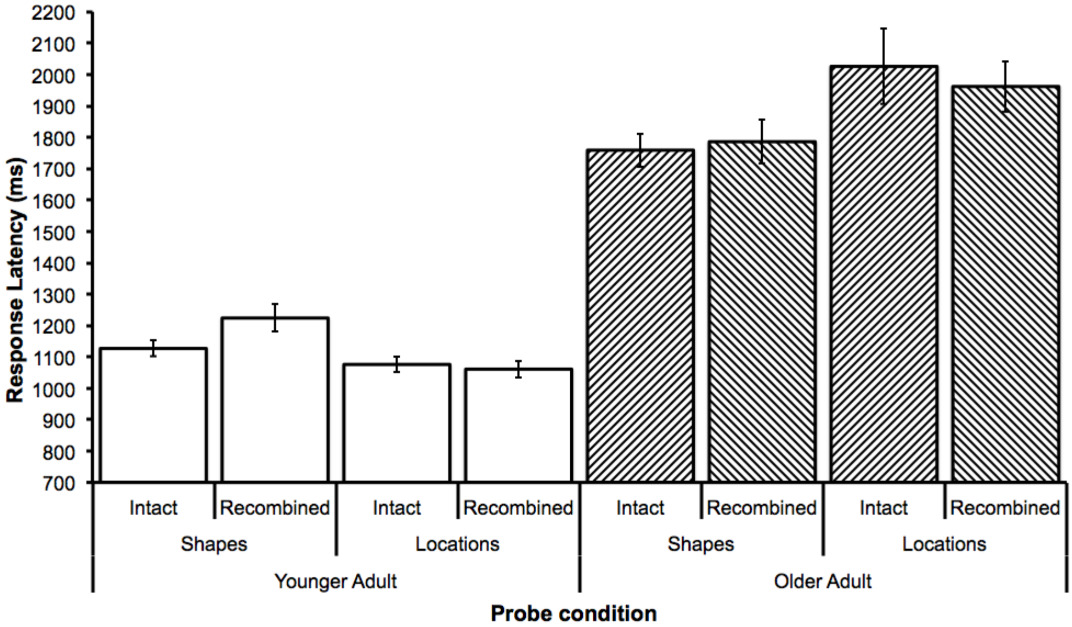


Figure 3.6. Younger and older adult mean reaction time (milliseconds) for intact and recombined probes as a function of attended feature. Bars represent one standard error of the mean.

Younger adults and binding (a)symmetry: Visuo-spatial features

Accuracy: A repeated measures ANOVA as in Experiment 6, conducted on accuracy showed a no main effect of probe type, F (1,34) = 3.50, MSE = 348.86, p = .07, ηp^2 = .09, BF_{10} = 0.55, with performance in the intact probe condition (M = 74.91, SD = 10.83) better than that in the recombined condition (M = 72.43, SD = 9.25) though the insensitive Bayes factor in fact tends toward support for the null; a significant main effect of relevant feature, F (1,34) = 16.71, MSE = 3008.58, p < .001, ηp^2 = .33, BF_{10} = 7066.28, whereby accuracy was greater in the locations condition (M = 84.94, SD = 15.77) than in the shapes condition (M = 73.67, SD = 10.08), and no interaction between factors, F (1,34) = 0.20, MSE = 15.78, p = .66, ηp^2 = .006, BF_{10} = 0.25.

Reaction Time: An ANOVA as above on reaction time showed no main effect of probe type, F (1,34) = 1.36, MSE = 58589, p = .25, ηp^2 = .04, BF_{10} = 0.28; a significant main effect of relevant feature, F (1,34) = 5.73, MSE = 400929, p = .02, ηp^2 = .14, BF_{10} = 4.21, whereby the location task (M = 1069ms, SD = 307ms) elicited faster reaction times than the shapes task (M = 1176ms, SD = 421ms); and no interaction between factors, F (1,34) = 1.95, MSE = 107088, p = .17, ηp^2 = .05, BF_{10} = 0.57. In sum, younger adult accuracy measures suggest marginal (and non-significant) evidence for binding, though this did not vary with attended feature thereby suggesting symmetry in feature binding, rather than the predicted asymmetry. In addition, accuracy measures suggested inferior performance in the shapes condition compared to the locations condition, a pattern which was matched in the response latency measures with faster responses recorded in the locations condition than in the shapes condition. Finally, response latencies did not provide evidence for binding in the younger adult sample.

Older adults and binding (a)symmetry: Visuo-spatial features

Accuracy: As above the repeated measures ANOVA, conducted on accuracy showed no main effect of probe type, F (1,21) = 3.49, MSE = 816.2, p = .08, ηp^2 = .14, BF_{10} = 1.10; and no significant main effect of relevant feature (F(1,21) = 0.80, MSE = 248.9, p = .38, ηp^2 = .04, BF_{10} = 0.35). The relevant feature by probe type interaction was however, significant (F(1,21) = 5.92, MSE = 654.5, p = .02, ηp^2 = .22, BF_{10} = 0.97), although the Bayes factor is insensitive. Further tests decomposing the significant interaction between relevant feature and probe type showed no evidence for binding in the shapes task ($t(21) = 0.24$, p = .81 $d = 0.05$, $BF_{10} = 0.23$); however there was evidence for binding in the locations task (t(21) = 2.35, $p = .03$, $d = 0.5$, $BF_{10} = 2.08$), although the Bayes factor here only tends toward support for a difference while remaining insensitive. Thus, according to the analysis of accuracy, older adults display an unpredicted isolated binding effect in the attend locations task that was absent in the attend shapes task (see figure 3.7.)

Reaction Time: The ANOVA on reaction time showed no main effect of probe type (F (1,21) = 0.03, $MSE = 7622$, $p = .87$, $\eta p^2 = .001$, $BF_{10} = 1.12$); or of relevant feature, ($F(1,21) = 3.18$, $MSE = 1.08^{e+7}$, $p = .09$, $\eta p^2 = .13$, $BF_{10} = 0.36$); and no interaction between factors, F (1,21) = 0.15, MSE = 45046, $p = .70$, $\eta p^2 = .007$, $BF_{10} = 1.04$.

In sum, older adult accuracy measures are suggestive of binding asymmetry whereby binding between shape and location did not occur under instructions to remember shapes, but did occur under instruction to remember locations. This is the opposite of that typically shown by younger adults (Campo et al., 2010; Elsley & Parmentier, 2015).

Overall Experiment 7 failed to demonstrate the predicted binding asymmetry in respect of younger adults, but showed an unanticipated asymmetry by the older adults in a direction opposite of that typically shown by younger adults.

3.3.3 Discussion

Experiment 7 aimed to replicate the procedures used in Experiment 6 only using visuo-spatial (shapes and locations) stimuli. The reason for this change was to align Chapter 3 with the rest of this thesis but one expected knock-on effect would be to take performance away from ceiling (a problem suffered by Experiment 6). Our predictions were as in Experiment 6: younger adults were predicted to display the established binding asymmetry whereby they should demonstrate a binding effect (intact over recombined probe advantage) in the shapes condition but not in the locations condition. Conversely, following the outcomes of Experiment 6, predictions regarding older adults were harder to make. On the one hand, older adults were predicted to show no effect of probe type in either relevant feature condition based on the observation that they typically having trouble binding features incidentally (Chee et al., 2006). Alternatively, based on performance displayed in Experiment 6, we might expect older adults to show evidence for binding regardless of which feature is attended voluntarily. Neither prediction was fully supported. Younger adults showed no evidence of binding in either feature condition while older adults showed the predicted null effect in respect of binding objects to locations in the shapes condition, but displayed an unanticipated binding effect in the locations task. Thus, older adults provide evidence for binding asymmetry, but not in a way that has been established in previous work for younger adults.

Binding (a)symmetry and younger adult performance

The lack of a binding effect (intact/recombined probe advantage) for younger adults in the shapes task is somewhat surprising given the prior demonstrations of this effect in other studies (Campo et al., 2010, Elsley & Parmentier, 2015). While the present study lacked a response time limit imposed by Campo et al. (2010), Elsley and Parmentier (2015) did not use a response time limit either and demonstrated the same asymmetry as Campo et al. (2010), suggesting this methodological difference cannot explain the performance differences between the experiments reported here and existing work. The second key difference between this study and previous work was the use of shapes rather than the more typical use of letter stimuli. As mentioned in the discussion of Experiment 6, the use of shapes here was designed to both make Experiment 7 more difficult (as a response window would have) and make the study more comparable to the others reported in this thesis.

Binding asymmetry and older adult performance.

Older adult accuracy data indicated no evidence for binding in the shapes task (as predicted based on evidence suggesting that older adults are impaired in their use of contextual information as a cue for recall) but a marked binding effect in the locations task. Thus, their memory for locations was clearly affected by irrelevant changes of shape. While explanations for this effect are post-hoc, seemingly similar findings have been demonstrated by Connelly and Hasher (1993) and may be explained if, instead of focusing on binding performance, one considers the task in terms of the ability to inhibit irrelevant features from stored VSTM representations. Connelly and Hasher (1993) used a flanker task to show younger adults were able to suppress identity distractors (distractors that shared visual information with the target) and location distractors (distractors that shared spatial location information with the target), but older adults were only able to suppress location based distractors and not identity based distractors suggesting that in more advanced age, attention is particularly drawn by object identity resulting in the inability to inhibit such information even when it is not task relevant. Thus, the isolated effect of binding in the locations task for older adults could potentially reflect their inability to inhibit visual features from stored spatial representations, in line with Connelly and Hasher's (1993) suggestion of an impaired inhibitory function for identity information in advancing age. Why this effect is only present in Experiment 7 and not Experiment 6 is difficult to explain. Nevertheless, as a fruitful avenue for further discussion, potential impairments in feature inhibition in older adults are discussed below.

Older adults and feature inhibition

The Inhibitory Deficit Theory (Lustig, Hasher & Zacks, 2007) suggests that ageing weakens the inhibitory processes that control which information enters or leaves working memory, leaving older adults unable to filter which information is processed. For instance, Schiavetto, Köhler, Grady, Winocur and Moscovitch (2002) had younger and older adults engage in an object matching task, an object retrieval task, a location matching task and a location retrieval task, while undergoing a PET scan. These tasks consisted of viewing an array of three objects and identifying whether a following array was the same or different on the basis of the task relevant feature. Younger adult scans suggested that they were able to selectively process the task relevant feature while ignoring the task irrelevant feature. With older adults activation remaining constant in both location and object regions regardless of which element participants were instructed to focus upon. This finding suggests that older adults have a reduced capacity for directed attention and may indicate that, in terms of Experiment 7 that older adults may have had difficulty in inhibiting the shape features from the location representations. Linking back to Connelly and Hasher (1993), this appears to be particularly apparent when object identity must be inhibited. Thus, older adult performance here may be the result of a different memory strategy enforced by a reduction in attentional specificity (Schiavetto et al., 2002) induced by impaired inhibitory processes.

If binding asymmetries arise as a consequence of inhibitory processes (with some features easier to inhibit from representations than others), the typical asymmetry finding in younger adults (Campo et al., 2010; Elsley & Parmentier, 2015) may be a consequence of younger adults being unable to suppress object location from a memory representation of object identity, while they can readily suppress object identity information from their representations of spatial location. In perhaps the most direct recent comparison for this study, Elsley and Parmentier (2015) demonstrated this binding asymmetry in younger adults remembering arrays of letters in locations across an attend letter and an attend locations task. Using a paradigm also based on Campo et al. (2010), in addition to demonstrating binding asymmetry, Elsley and Parmentier (2015) further showed that bindings between letters and locations persist for at least 15 seconds after the presentation of the array. Important to note though is that although letter/location bindings are sensitive to changes in location, letter recall does not entirely hinge upon location being maintained between array and test, perhaps suggesting that object features are partially stored independent of location. This supports Triesman and Zhang (2006) who argued that when objects are attended, surface features, such as colour or shape, and location features, are spontaneously integrated. In Treisman and Zhang's (2006) study, arrays of three coloured shapes were displayed for 150ms, then after a delay that varied from 0.3 seconds to as long as 6 seconds, participants were tasked with deciding whether a probe array showed the same colour/shape bindings as before. In addition, the locations of the shapes could be either maintained or changed. Where the objects remained in their original location, memory performance was consistently more accurate, though crucially colour/shape combinations could still be effectively recalled when the location changed. Therefore, although bindings between objects and locations appeared obligatory, objects could be recalled independent of location.

Thus, if bindings between surface features and locations occur spontaneously, and persist over time, older adults may approach this task in a different fashion to younger adults, perhaps not processing location under instruction to remember shapes (in line with the FMR adaptation findings of Chee et al., 2006) but being unable to suppress the processing of object identity under instructions to remember locations (as seen in the flanker tasks used by Connelly and Hasher, 1993); thus creating the opposite pattern of performance. Interestingly, this inhibition process could itself be effortful, (Conway & Engle, 1994; Roberts, Hager, & Heron, 1994), which could, linking back to the *ageing-attention hypothesis* assessed in Chapter 2, render older adults unable to inhibit the irrelevant shape features in Experiment 7. The hypothesis, however, would need to be amended. Specifically, rather than restricted attentional resources in older age preventing the binding objects to locations, it may instead create the unwanted binding of locations to objects due to an inability to filter and inhibit task irrelevant information. While we note that the performance of younger adults was not as expected in either Experiment 6 (where they showed evidence for binding regardless of which feature was attended voluntarily) or Experiment 7 (where they showed only marginal evidence for binding in both conditions), we feel that assessing the role of attentional resources during incidental binding, and it's potential impact on the symmetry of bound representations is a logical next step for empirical investigation. Accordingly, Experiment 8 assessed the impact of dividing attention on the (a)symmetry of bound representations. The experiment was a methodological replication of

Experiment 7 with the addition of an attentional load task (as in Chapter 2). If asymmetries arise as a consequence of an effortful inhibition process for task-irrelevant features, we may expect to find binding in both attended feature tasks (shapes and locations) in Experiment 8 under cognitive load, and no evidence for binding in either attended feature task under conditions of low cognitive load. Although this runs in contrast to the established explanations in this paradigm (e.g. Campo et al., 2010, Elsley & Parmentier, 2015), Experiments 6 & 7 suggest that the classic binding asymmetry may arise under particular circumstances.

3.4 Experiment 8: Binding (a)symmetry and attention: visual-spatial features.

Experiment 8 formed a direct replication of Experiment 7 with only younger adult participants completing the task twice, each time with a concurrent task representing different levels of cognitive load. In the low cognitive load condition, they were required to repeat a number presented to them at the start of each trial out loud; while in the high cognitive load condition, they were required to count backwards in 3s from the number given at the start of each trial. As such, Experiment 8 builds on prior work in a number of ways. Firstly, it provides an assessment of the impact of cognitive load on incidental binding ability (rather than intentional binding ability traditionally assessed by existing research: e.g., Allen et al., 2006; Elsley & Parmentier, 2009). Second, it will assess the impact of divided attention on the (a)symmetry of bound representations; and thirdly the data gleaned may be directly compared to that from older adults in Experiment 7 in order to see whether younger adults may mimic older adult performance under conditions of high cognitive load.

In line with Campo et al. (2010) and Elsley and Parmentier (2015: although c.f., the results of Experiments 6 and 7), performance under low cognitive load is predicted to produce the standard binding asymmetry, whereby evidence for binding (intact over recombined probe advantage) is gained in the shapes condition but not the locations condition. On the basis that the lack of binding in the locations condition is due to an effortful inhibition process for the shape features (Conway & Engle, 1994; Roberts, Hager, & Heron, 1994), we would further predict evidence for binding in both the locations and the shapes task under conditions of high cognitive load.

3.4.1 Method

3.4.1.1 Participants

Twenty seven younger adult participants (18 females, 9 males) with a mean age of 21.36 (SD = 2.04) completed this study for course credits or a small honorarium. The study took approximately 65 minutes and all participants report normal, or corrected to normal vision.

3.4.1.2 Materials

As in Experiment 7, the stimuli consisted of 8 shapes of the type used in Experiments 4 and 5 (Chapter 2), previously piloted to ensure low nameability (Chuah et al., 2004). Each stimulus was presented in white outline on a black background and each within a l.87° x l.87° white frame so as to reduce variations in spatial configurations between the shapes (Delvenne et al., 2002). On each trial, the TBR array consisted of four stimuli (shapes sampled without replacement) presented in a circular array of eight possible locations each 3.63° from the screen centre, on a 20" monitor. The probe consisted of a single shape presented in one of the eight locations. The task was purpose written using Matlab and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007). Responses were collected via standard keyboard.

3.4.1.3 Design

This experiment used a within subjects design with all participants completing the experiment both under low cognitive load (repeating a number) and high cognitive load (counting backwards in threes). Variables are otherwise as in Experiment 7, with the exception of the age group variable which is not present here.

3.4.1.4 Procedure

Experiment 8 closely followed the procedure set out in Experiment 7, with the exception that each participant now completed the shape and location conditions twice, once under low cognitive load (concurrent articulation of the number that appears at the beginning of each trial), and once under high cognitive load (counting backwards in threes from the number that appears at the beginning of each trial). Articulation followed the procedures used in

Experiments 2-4 and was monitored by the experimenter. Cognitive load order, and attended feature was counterbalanced between participants.

3.4.1.5 Data Analysis

Data were analysed in accordance with both accuracy (% correct) and reaction time (for correct responses only, measured in ms) measures. Below we present performance for intact and recombined probes as a function of relevant feature and cognitive load. However, supplementary analyses of all positive probe types and negative probes can be found in Appendix C.

3.4.2 Results

Binding as a function of attended feature and cognitive load

Accuracy: A 2 (Load: low, high) x 2 (Relevant Feature: shape, location) x 2 (Probe Type: intact, recombined) repeated measures ANOVA conducted on accuracy showed no main effect of load, F (1,24) = 3.50, MSE = 1312.84, p = .07, ηp^2 = .0.13, BF_{10} = 1.18, whereby performance in the low load condition (M = 77.03, SD = 14.22) was better than that in the high load condition (M = 71.91, SD = 11.59) although the Bayes factor was insensitive to a difference; a significant main effect of probe type, F (1,24) = 8.57, MSE = 844.84, p = .007, ηp^2 = .26, BF_{10} = 0.55, with performance in the intact probe condition (M = 76.52, SD = 11.33) better than that in the recombined probes condition (M = 72.41, SD = 11.78), though again it must be noted that Bayes factor tended toward support for the null here; and a significant main effect of relevant feature, F (1,24)

= 23.61, *MSE* = 12953.83, $p < .001$, $\eta p^2 = .50$, $BF_{10} = 1.75^{e+10}$, whereby fewer errors were committed in locations condition (*M* = 82.52, *SD* = 7.91) than in the shapes condition (*M* = 66.42, *SD* = 17.81). There was no interaction between relevant feature and load, *F* (1,24) = 1.98, *MSE* = 415.91, $p = .17$, $\eta p^2 = .08$, $BF_{10} = 0.43$), no interaction between probe type and load, *F* (1,24) = 0.84, *MSE* = 102.16, $p = .37$, $\eta p^2 = .03$, $BF_{10} = 0.23$, and no interaction between relevant feature and probe, *F* (1,24) = 2.64, *MSE* = 309.86, $p = .12$, $\eta p^2 = .10$, $BF_{10} = 0.36$. The three-way interaction, was similarly non-significant, *F* (1,24) = 1.40, *MSE* = 156.75, $p = .25$, $\eta p^2 = .06$, $BF_{10} = 0.40$. Data are displayed in Figure 3.7.

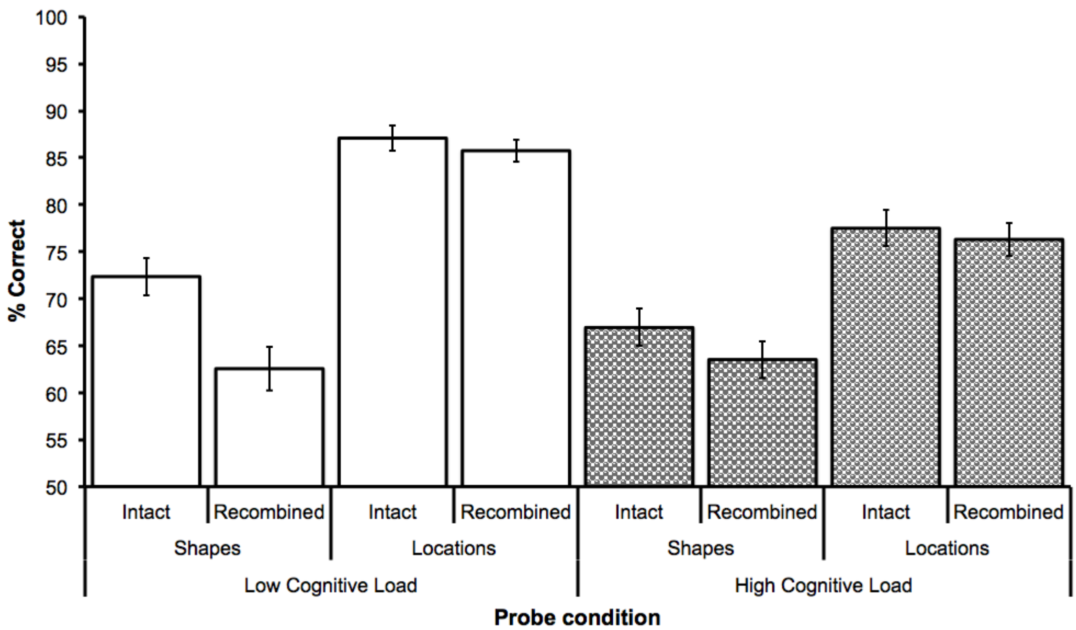


Figure 3.7. Mean accuracy (% correct) for intact and recombined probes as a function of attended feature and cognitive load. Bars represent one standard error of the mean.

Reaction Time: A similar ANOVA conducted on reaction time data showed a significant main effect of load, F (1,24) = 8.50, MSE = 1.16^{e+7}, p = .008, ηp^2 = 0.26, BF_{10} = 24.17, whereby responses in the low load condition (M = 963.18, SD = 225.82) were faster than that in the high load condition (M = 1115.27, SD = 369.50); no main effect of probe type, F (1,24) = 3.10, MSE = 62269.21, p = .09, ηp^2 = .11, BF_{10} = 0.26; and no main effect of relevant feature, F (1,24) = 0.10, MSE = 7775.04, p = .76, ηp^2 = .004, BF_{10} = 0.16. In addition, there was no interaction between relevant feature and load, F (1,24) = 2.15, MSE = 121869.85, p = .16, ηp^2 = .08, BF_{10} = 0.66, no interaction between probe type and load F (1,24) = 0.05, MSE = 1235.05, p = .82, ηp^2 = .002, BF_{10} = 0.21, and no interaction between relevant feature and probe type, F (1,24) = 2.24, MSE = 19900.13, p = .15, ηp^2 = .09, BF_{10} = 0.25. The three-way interaction was also non-significant, F (1,24) = 0.01, MSE = 91.12, p = .939, ηp^2 < .001, BF_{10} = 0.28). Data are illustrated in Figure 3.8.

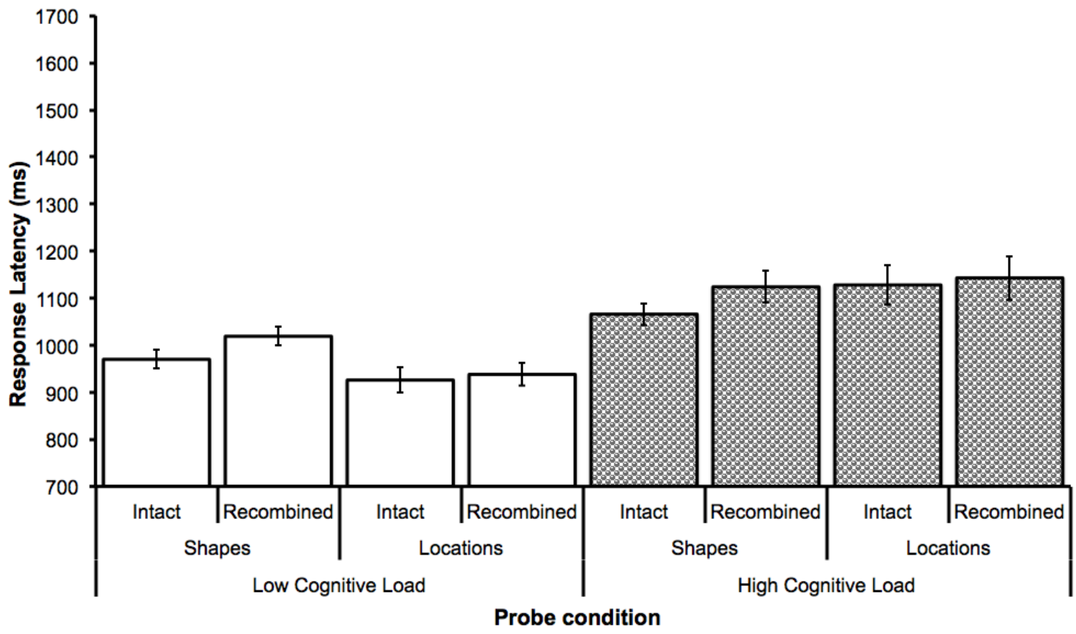


Figure 3.8. Mean reaction times (milliseconds) for intact and recombined probes as a function of attended feature and cognitive load. Bars represent one standard error of the mean.

In sum, omnibus analyses suggest a minimal effect of cognitive load on accuracy, but a much stronger effect on reaction times, whereby in both measures, performance under low cognitive load was better than that under high cognitive load. Although there was a significant effect of probe type in respect of accuracy, Bayes factors were insensitive though tending toward support for the null hypothesis, and there was no effect here for reaction times. Interactions were non-significant throughout. Given the prediction that asymmetry should occur in the low cognitive load condition (see Campo et al., 2010; Elsley & Parmentier, 2015), and the importance of replicating this finding for drawing conclusions from the addition of the high cognitive load condition, each cognitive load condition should be analysed independently.

Binding (a)symmetry under low cognitive load

Accuracy: A repeated measures ANOVA, conducted on accuracy measures in the low cognitive load condition showed a significant binding effect, $F(1,24) = 10.547$, $MSE = 767.29$, $p = .003$, $\eta p^2 = .31$, $BF_{10} = 0.77$, with performance in the intact probe condition ($M = 79.80$, $SD = 18.28$) producing better accuracy than the recombined probe condition ($M = 74.26$, $SD = 21.32$) though the Bayes factor is insensitive; and a significant main effect of relevant feature, $F(1,24) = 35.02$, $MSE = 9006.01$, $p < .001$, $\eta p^2 = .59$, $BF_{10} = 2.24^{e+9}$, with lower accuracy in the shape condition ($M = 67.54$, $SD = 21.59$) relative to the locations condition ($M = 86.52$, $SD = 21.32$). Finally, there was a significant interaction between factors, $F(1,24) = 5.88$, $MSE = 453.69$, $p = .02$, $\eta p^2 = .20$, $BF_{10} = 1.10$ (though the Bayes factor is insensitive with the null and the alternative almost equally likely). Further tests decomposing the significant interaction between probe type and attended feature indicated a significant binding effect in the shapes task, t(24) = 3.53, p = .002, d = 0.71, $BF_{10} = 21.51$, but not in the locations task, t(24) = 0.62, p = .54, d = 0.12, $BF_{10} = 0.25$. This pattern of data is consistent with the observation of a binding asymmetry reported elsewhere.

Reaction Time: An ANOVA as above on reaction time showed no main effect of probe type, $F(1,24) = 2.41$, $MSE = 22983$, $p = .13$, $\eta p^2 = .09$, $BF_{10} = 0.33$; or of relevant feature, $F(1,24) = 2.41$, $MSE = 95605$, $p = .13$, $\eta p^2 = .09$, $BF_{10} = 1.63$; and no interaction between these factors, $F(1,24) = 0.69$, $MSE = 8649$, $p = .41$, $\eta p^2 = .03$, $BF_{10} = 0.34$.

Binding asymmetry under high cognitive load

Accuracy: A similar ANOVA to those above conducted on accuracy measures in the high cognitive load condition showed no main effect of probe type, F (1,24) = 1.23, MSE = 179.71, p = .28, ηp^2 = .05, BF_{10} = 0.27; a significant main effect of relevant feature, F (1,24) = 8.70, MSE = 4363.73, p = .007, ηp^2 = .27, BF_{10} = 280.82, whereby performance in the shape condition (M = 65.3, SD = 19.32) was poorer than performance in the location condition (M = 78.51, SD = 16.89). Finally, there was no significant interaction between factors, F (1,24) = 0.09, MSE = 12.92, p = .77, ηp^2 = .004, BF_{10} = 0.28. Thus, the binding asymmetry present in the low load condition for accuracy measures was absent under high cognitive load. Confirming this, planned contrasts show no evidence for binding in the shapes task, (t(24) = 1.03, p = .32 d = 0.21, BF_{10} = 0.34) and no evidence for binding in the locations task, (t(24) = 0.55, p = .59, d = 0.11, BF_{10} = 0.24). Thus, according to these comparisons, there is an isolated effect of binding in the shapes task under low cognitive load, that is not present in the locations task in that condition, or in either task in the high cognitive load condition.

Reaction Time: The reaction time ANOVA showed no main effect of probe type, F (1,24) = 1.18, MSE = 40522, p = .29, ηp^2 = .05, BF_{10} = 0.30; or of relevant feature, F (1,24) = 0.35, MSE = 34040, p = .56, ηp^2 = .01, BF_{10} = 0.29; and no interaction between factors, F (1,24) = 0.97, MSE = 11342, p = .34, ηp^2 = .04, BF_{10} = 0.31.

The results of Experiment 8 indicate that under low cognitive load, incidental binding occurs between shape and location only when shapes are task relevant, with no binding occurring when locations are task relevant; thus displaying the binding asymmetry previously shown between letters and locations by Campo et al., (2010) and Elsley and Parmentier (2015). Additionally, under high cognitive load, binding between shapes and locations is not present irrespective of which feature is task relevant.

3.5 Discussion

Experiment 8 investigated the impact of an attentional load on binding asymmetry. The experiment was motivated by the finding in Experiment 7 where older adult performance was suggestive of an impairment of feature inhibition. Under instructions to remember shapes, older adults showed no evidence of binding between shapes and the task irrelevant feature of location. However, under instruction to remember locations, there was evidence that locations were bound to shapes. In searching for an explanation it was found that Connolly and Hasher (1993) had shown a similar pattern of results using flanker tasks, where older adults were able to suppress distractors that shared locations with task critical objects, but were not able to suppress distractors that shared shapes with task critical objects, suggesting that when object location was task relevant, older adults incidentally bound location to identity; seemingly in much the same manner as older adults in Experiment 7 here.

There were two main findings. First, under low cognitive load, participants produced a pattern of accuracy performance consistent with binding asymmetry. That is, there was evidence for binding in the shapes condition but not the locations condition, replicating work reported elsewhere for verbal-spatial features (Campo et al., 2010; Elsley & Parmentier, 2015: though it must be noted that the three-way interaction between cognitive load, relevant feature and probe type was not significant so the finding should be treated tentatively). Under high cognitive load, however, the binding effect present in the shapes task under low cognitive load disappeared (and there was no evidence for binding in the locations task). Although a direct comparison between the binding difference (the difference between intact and recombined probe performance) in each cognitive load condition was not conducted, the difference between the Bayes factors provides stark evidence for this assertion. Bayes factors indicated strong evidence for a difference in accuracy between the intact and recombined probe types in the low cognitive load condition, but indicated favour for the null in respect of the same comparison in the high cognitive load condition. This suggests that incidental binding between an object and its position in space may be an effortful process.

These findings run contrary to our predictions whereby we speculated that the performance pattern of older adults in Experiment 7. where participants showed no evidence of binding between shapes and locations under instruction to remember shapes but evidence of binding under instruction to remember locations, may have been accounted for by an impaired ability to inhibit shape representations from stored location information, an inhibition process which, if effortful (e.g., Conway & Engle, 1994) should be disrupted under divided attention conditions. Reaction time analysis was not contradictory in numerical terms for both the low of high cognitive load conditions, and showed no clear effect overall.

In summation, Experiment 8 demonstrates that although the incidental binding of objects to locations appears to be obligatory, it is also effortful (see also Elsley & Parmentier, 2009). These issues are discussed in detail in the Chapter discussion below.

3.6 Chapter Three General Discussion

The aim of Chapter 3 was to investigate changes in incidental feature binding ability as a consequence of normal ageing. Building on the now established binding asymmetry (the observation that objects bind to locations when object identity is task-relevant but not when object locations are task relevant: Campo et al. 2010; Elsley & Parmentier, 2015), we reasoned that older adults may differ to their younger counterparts in the symmetry of bindings in this type of task. This suggestion was based on existing evidence suggesting that firstly, older adults are impaired in terms of their ability to bind objects to locations (e.g. Cowan et al., 2006), and secondly, that older adults seemingly do not use contextual information as an organisational cue in working memory (Meulenbroek et al., 2010). Thus, Experiment 6 formed a direct replication of Campo et al.'s (2010) task assessing the symmetry of binding between verbal-spatial features in younger and older adults. The results of Experiment 6, as noted in the discussion above, suffered from a severe ceiling effect and failed to replicate established findings in respect of incidental object-location binding. Rather than the asymmetry shown by Campo et al. (2010) and Elsley and Parmentier (2015), Experiment 6 showed an overall binding effect in both the object (letter) and location conditions, with no apparent difference between the younger and older adult groups. Given the issues noted in terms of the low difficulty of the task compared to Campo et al. (2010), it seems likely that these findings are spurious.

We then conducted Experiment 7 in which the basic task from Campo et al. (2010) was replicated, but this time using abstract polygonal shapes were used with the aim of both drawing performance away from the ceiling observed in Experiment 6, and moving this study of incidental binding, to be more in line with the study of intentional binding in Chapter Two. Performance here did differ in respect of age group. Younger adults performed in a manner similar to that seen in Experiment 6 showing no binding asymmetry, but rather a general binding effect between shapes and locations. Older adults however, showed a clear binding asymmetry that was the opposite of that which is ordinarily shown in this paradigm (Campo et al., 2010; Elsley & Parmentier, 2015). Thus, older adults showed no evidence of binding when tasked with remembering shapes, but clear evidence of binding in respect of location memory. The lack of binding asymmetry in the younger adult data raises a number of questions.

Finally, in Experiment 8 we reasoned that perhaps older adult performance could be explained in terms of impaired inhibition. On the basis that inhibition processes have been shown to be cognitively demanding (Conway & Engle, 1994; Roberts, Hager, & Heron, 1994), Experiment 8 again utilised the paradigm of Campo et al. (2010) but this time with just younger adults and the addition of a cognitively demanding concurrent task. Participants completed the task as in Experiment 7, but this time either under low cognitive load (repeating a double digit number for duration of each trial) or under high cognitive load (counting backwards in threes from a double digit number for the duration of each trial). Here, under low cognitive load, younger adults displayed the established binding asymmetry with evidence of binding between shapes and locations when instructed to remember shapes, but not when instructed to remember locations. In the high cognitive load condition, there was no evidence of binding in either the remember shapes, or remember locations memory condition. Therefore, the incidental binding of shapes and locations appears to be a resource demanding and obligatory, task. This of course contrasts with typical models of cognitive control, which commonly contend that in terms of processing, a task can be resource demanding, or obligatory, never both (e.g. Miyake & Friedman, 2012). As a result a more likely explanation may be that this seemingly incidental binding is a result of post conscious automaticity (Bargh, Schwader, Hailey, Dyer, & Boothby, 2012). This essentially means that there is a conscious strategic decision to bind objects to locations, and this binding then proceeds in manner that can appear automatic. Thus the initial strategic decision and application of attention is effortful, but the subsequent processing proceeds as though it is not.

It must also be addressed is that the performance of younger adults in Experiment 7, does not match that of the younger adults in the low cognitive load condition of Experiment 8. This is in spite of there being no difference in the experimental procedures between these groups. The first suggestion must be that the so-called binding asymmetry is simply not a robust effect, which of course casts a degree of doubt on conclusions drawn from the data presented here. There is little notable difference in the demographics of these groups, and although some of those in Experiment 8 completed this condition after a high cognitive load condition (due to counterbalancing), there was no identifiable effect of task order. In light of the published literature demonstrating this asymmetry, and the replication of that asymmetry in Experiment 8, the younger adult data in Experiment 7, in short, appears to be something of an anomaly.

3.6.1 Incidental Binding and Ageing

In comparing the performance of older adults in Experiment 7, and the high cognitive load condition of Experiment 8, performance in the shapes condition is the same, while performance in the locations condition differed, with the older adults showing an unanticipated intact/recombined advantage, while the high cognitive load younger adult group did not. The first notion to be considered is that the concurrent task of counting backwards in threes did not impair younger adult performance enough to elicit the pattern of location performance seen in older adults. If we assume that each relevant feature condition is cognitively tackled in the same manner, then there is no viable explanation of incidental feature binding that encompasses the performance of younger adults in Experiment 8 (both under low and high cognitive load) and older adults in Experiment 7. As previously discussed, the evidence in Experiment 8 supports incidental binding as occurring at the encoding stage. Higher cognitive load can thus only logically reduce the intact/recombined advantage rather than induce one as would have to be the case to produce performance among younger adults that matches that of older adults. The only caveat here is that if one were to posit that the shape task is fundamentally different to the locations task; with the shape task representing the binding of objects to locations at the encoding stage, and the locations task representing the inhibition of the irrelevant shape feature which could occur at either the encoding or retrieval stage. Then the addition of a cognitively demanding concurrent task should both remove the intact/recombined advantage in the shape task, and induce this advantage in the locations task. If this were the case, then it is possible that the use of a more demanding concurrent task could induce the performance of older adults in a younger adult population. However, the MEG findings from Campo et al. (2010) work against this suggestion, as activity differed only in terms of early oscilatory activity that occurred exclusively in their letters condition (equivalent to shapes here) and was thought to be representative of binding processes. Thus under the assumption that both relevant feature conditions represented are completed using the same cognitive processes in younger adults, the *ageing-attention hypothesis* can be rejected in the case of incidental object-location binding.

The rejection of restricted attention as an explanation of older adult incidental binding performance leaves two further possibilities to be addressed. Firstly, one might suggest that binding ability declines independently of attentional resources in advanced age, or at least that the decline in binding ability is multi-causal, with attention playing only a minor role. This is not without precedence in the literature with Kilb and Naveh-Benjamin (2007) showing both younger and older adults equally affected by a reduction in available attention, in their memory for individual items (words) and for associations between word pairs. Older adults though, did show a specific deficit in memory for word associations that appeared to be independent of available attention. While this is to some extent supported by the differences between older adults and younger adults across Experiments 7 and 8, this still assumes that older adults are, cognitively speaking, attempting to complete the task in the same way as younger adults.

The second alternative to restricted attention as an explanation of older adult incidental binding performance is that, as suggested in the discussion of Experiment 7, older adults may simply be completing the task differently to younger adults. Rather than processing the associations between features of individual objects, older adults may instead be concentrating on the task relevant feature and processing the irrelevant feature as though it were a distractor in a flanker task, essentially turning the task into one where the irrelevant distractor must be inhibited. Interestingly, it may be the case that the inhibition required to do the task in this way, is itself be demanding on attentional resources. With Connolly and Hasher (1993) showing that older adults can inhibit location based distractors but not object based distractors, while younger adults are able to inhibit either, this creates the question of whether younger adults completing a flanker task, would produce similar performance to older adults, if they did so while completing a concurrent cognitively demanding task.

3.6.2 Incidental Binding and Attention

In terms of the influence of attentional resources, Experiment 8 demonstrated that even seemingly obligatory binding between shapes and locations is effortful. This is supportive of Elsley and Parmentier (2009) who, using a somewhat different paradigm, first demonstrated that the addition of a concurrent cognitively demanding task leads to a reduction in binding between object and location. In Elsley and Parmentier's (2009) task, participants were shown an array similar that used in Experiments 6-8 here, and instructed to remember both the letters and locations, but to ignore to the combinations. As such, feature bindings were not required for the completion of the task, and, in fact, were even detrimental to accuracy as, in the event that binding occurs, accurate responses to recombined probes require the participant to first decompose the constituent features. They completed the task under low and high cognitive load conditions, with the low load condition showing a clear binding effect (where intact probes elicited higher accuracy than recombined probes), and a marked reduction of this binding under higher cognitive load (a vastly reduced difference between intact and recombined probes that may constitute the complete removal of incidental letter-location binding). Experiment 8 builds on this through the use of Bayesian statistics (based on a priori predictions) that show the near total removal of the incidental binding effect under high cognitive load. As such, we can conclude that incidental binding between objects and locations is effortful.

3.6.3 Summary

In sum, the experiments presented in this chapter illustrate firstly that there are differences in the incidental binding ability of older adults, whereby older adults do not show evidence of binding objects to locations when focusing upon object identity, but do seemingly bind identity and location when focusing on object location. Comparing Experiments 7 and 8 suggests it is unlikely that this difference occurs as a function of decreased attentional resources, and as such the *ageing-attention hypothesis* can be rejected. The *ageing-context hypothesis* however is not so easily resolved. It does seem likely that older adult performance occurs as a function of declined ability to process contextual information (Experiment 7), so in that respect, it is supported. What remains to be seen however, is whether older adults are still attempting to complete this paradigm in the same manner as younger adults, or whether they are cognitively treating this as a different task.

Chapter 4 will investigate this further by using a different incidental binding paradigm and comparing performance of younger and older adults.

Chapter Four. Binding Performance: Ageing and Effects of Incidental Changes in Relative and Absolute Location

4. Binding Performance: Ageing and the Effects of Incidental Changes in Relative and Absolute Location

4.1 Introduction

With the prior chapters indicating no deficit in the ability of older adults to bind objects to locations intentionally (Chapter 2) or incidentally (Chapter 3), Chapter 4 investigated whether there may be differences in the way in which older adults process spatial information during the representation of objects in VWM. One such difference may stem from the representation of objects in terms of their absolute spatial location versus their relative location, this suggestion is supported by the observation that objects are more easily and quickly remembered when its location relative to other nearby objects remains the same between array and test, even if the set of objects moves in terms of its absolute location (e.g. Olson & Marshuetz, 2005) and is discussed in detail below.

What type of spatial representation is used during object memory? Relative vs absolute spatial location.

Numerous investigations on how objects are processed and represented in memory have been conducted with younger adults (e.g. Jiang, Olson & Chun, 2000; Lin & He, 2012; Olson & Marshuetz, 2005), many of which appear to point to a distinction between the representation of objects in terms of their absolute and relative positions in space. Specifically, location in VSTM can be thought of in two ways; absolute location, and relative location. Absolute location is the location of an object based on a fixed point. In experimental terms, if one were to create grid references for a computer screen in a manner akin to latitude and longitude on a map, a location expressed in absolute terms would always appear at the same grid reference irrespective of its position compared with other objects. A relative location is one thought of in terms of its position in comparison with other objects. These other nearby objects form the context by which object location is identified. Returning to the analogy above, rather than being remembered in terms of a specific grid reference, in relative terms, a task critical object may be remembered as being to the left of object 2 and below object 3. As long as the object creates this context, its absolute location is not necessary or used in remembering its location.

Of particular note, Jiang, Olson and Chun (2000) performed a series of experiments investigating the relationship between the spatial configuration of an array of objects, and the visual features (colour and shape) of the objects held within that configuration. Using a change detection task, their Experiment 1 had participants shown an array of coloured objects, tasked with remembering only the colours. The probe consisted either of a single object (which was either the same colour as the object shown in that location during the memory array, or a colour not seen in the array), or they were presented with the complete array with participants responding to a cued object (and again this object was either the same colour as the object shown in that location during the memory array, or a colour not seen in the array). Participants performed significantly worse when a single probe was presented suggesting that the array was stored as a configuration rather than each being stored separately. Subsequent experiments investigated the manner of this configural storage. Key findings were that partial configuration information is not beneficial to object memory and that when the configuration was kept intact, but the distance between objects is altered (i.e., the configuration was expanded), performance remained at a level similar to when the original configuration was maintained. Changing the configuration though, has an adverse effect on performance.

Critically, Jiang et al. (2000) further showed that task-irrelevant changes to object locations negatively impacted upon item memory (e.g., for colours or shapes), providing evidence that memory for 'what' is linked to memory for 'where'; while the reverse relationship did not, by necessity, hold true – demonstrating binding asymmetry (discussed in detail in Chapter 3, see also Elsley & Parmentier, 2015; Campo et al., 2012). Taken together, these findings suggest that objects in an array are typically remembered in their positions relative to other presented objects. Changes to the absolute positions of items can be made with little impact upon item memory so long as the positions of those items relative to each other is preserved between display and test. Jiang et al.'s (2000) study suggests that the representation of location information is obligatory during visual object processing and that such processing preserves the configuration of an array.

A similar finding was observed in a more recent study by Olson and Marshuetz (2005) who investigated how younger adults judge the location of objects in a change detection task, manipulating the (task-irrelevant) location of objects against a simple background context consisting of a small white square (Sq1) that appeared within a larger grey square (Sq2). Olson and Marshuetz (2005; Experiment 1) tasked participants with remembering the identity of a single face over a short retention period; the face was presented in one corner of Sq1 which itself would appear in one of the four quadrants of Sq2. After the initial presentation of the face array there was a short delay, followed by a probe from one of three conditions: *No change*: where the probe was identical to the array; *global change*: where the face retained its location in Sq1, but Sq1 moved to a different quadrant of Sq2; *local change*: where the face moved to a different corner of Sq1, and Sq1 moved to a different quadrant of Sq2[5]. See figure 4.1. for array and probe examples.

[5] A "global" location change is perhaps best characterised as a change in *absolute location*; object location would thus be presumed to be judged in terms of its position within a retinotopic map of all that is in view (represented in Olson & Marshuetz's experiment by the large grey square). Applying this principle further, a "local" change in object location is therefore better characterised as a change in *relative location*; whereby object location is judged in terms of its position compared with nearby contextual features (the smaller white square in Olson & Marshuetz's experiment).

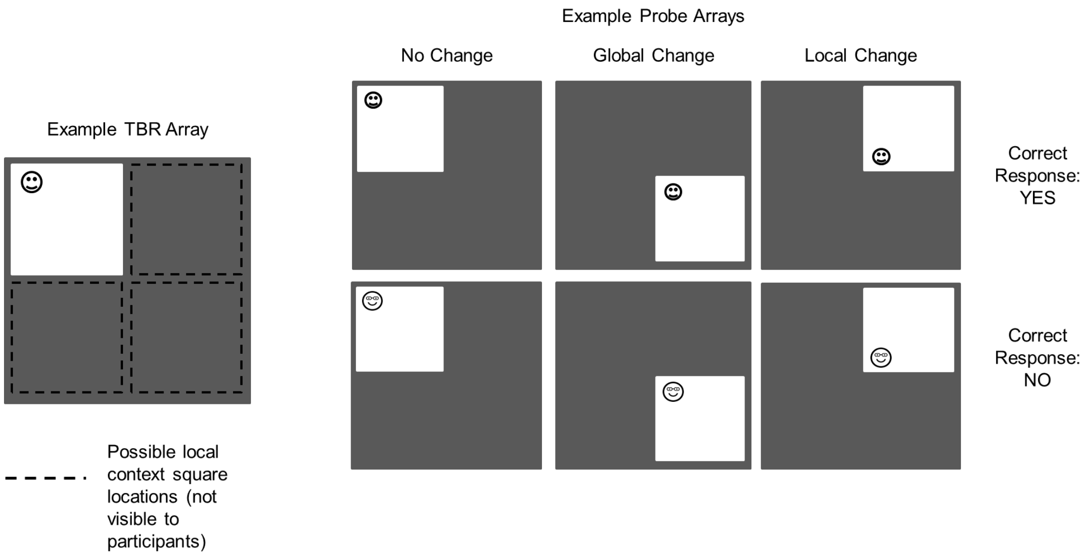


Figure 4.1. Example Array and probe conditions with indications of possible Sq1 and TBR object positions (note, face stimuli were photorealistic not the simplified images indicated here). Adapted from Olson and Marshuetz (2005).

Olson and Marshuetz (2005) found that a global (absolute) change in object location, produced reaction times similar to the no-change condition, while the local (relative) location change elicited slower reaction times than the no-change condition. This is argued to indicate that younger adults judge object location in terms its position relative to nearby contextual information, rather than their absolute position in space. Thus, younger adults appear to encode visually presented objects in positions relative to other objects in an array, perhaps as these items provide a frame of reference or sense of context. Critically for the purposes of the current chapter, there is evidence to suggest that older adults may treat contextual information differently to younger adults. On the one hand, older adults have been shown to be impaired with regard to binding objects to context (with spatial location acting as a key contextual cue: Meulenbroek et al., 2010: discussed in Chapter 3) while on the other hand, older adults have also been shown to be unable to appropriately inhibit task-irrelevant background context information when processing objects (Chee et al., 2006; Gazzeley et al., 2008). These issues are discussed in detail below.

Do older and younger adults use spatial information in the same manner as younger adults when representing objects in VWM?

While no study to date has directly addressed the question of whether older adults differ in their reliance on absolute versus relative spatial information during the processing of visual objects (a caveat to which the present study is addressed), there is evidence to suggest that older adults may be impaired during the processing of contextual information (e.g., Meulenbroek et al., 2010; Kessels et al., 2007). These studies, however, did not directly tease apart the influences of maintaining/changing the absolute versus relative spatial locations of objects. Perhaps even more tantalizingly, there is evidence to suggest that older adults may be impaired at inhibiting task-irrelevant contextual information. For instance, Gazzeley et al. (2008) sequentially presented face images alternating with landscape scene images. Instructions were given to either attend to the faces while ignoring the scenes, or to do the inverse. Findings from EEG recordings indicated that older adults experienced a deficit in targeted visual suppression in the early stages of visual processing. That is to say, during the initial processing of images, older adults were unable to filter out information that has been deemed irrelevant by prior instruction. This deficit was not present in the younger adults, who consistently were able to suppress processing of the irrelevant images.

Of more direct relevance, Chee et al. (2006) investigated older and younger adults' processing of objects and contextual information by instructing participants to attend to a specific part of an image consisting of an object (such as a tractor) placed upon a background landscape image, while ignoring the all areas of the image that do not contain the task relevant object. During the experiment, Functional Magnetic Resonance Adaptation (fMR-A) data was recorded. This is a form of functional brain imaging where specific neuron populations are identified in a similar manner to identifying regions of interest in classic fMRI, then stimuli are repeatedly presented until these populations of neurons adapt (alter from their resting state). Following this adaptation one property of the stimulus is adjusted; then if the neuron populations adapt, then one can see that these clusters of neurons are sensitive to that property of the image. If these neuron populations remain the same, then it can be said that these neurons are insensitive to that property of an image (Grill-Spector & Malach, 2001). In Chee et al.'s (2006) study, participants were presented with an object, such as a butterfly or telephone, placed on a background landscape image such as a rural scene. Instructions were either (1) remember the object in isolation while ignoring the background entirely, or (2) remember the combination of object and background. Under instruction (1) younger adults' fMR-A demonstrated selective processing of the object while ignoring the background. Performance under instruction (2) however showed a different pattern of activity indicating that the background image was processed in addition to the object stimulus. This demonstrates that when required, younger adults are able to selectively inhibit the processing of background contextual information. Conversely, older adults' fMR-A data showed patterns of activity consistent with the processing of the background context irrespective of the instructions given, suggesting again that older adults are unable to selectively inhibit the processing of background contextual information[6].

In sum, older adults appear to exhibit specific impairments in inhibiting the processing of background contextual information (Gazzeley et al., 2008; Chee et al., 2006) in tasks requiring memory for objects. One potential explanation for this is that older adults are less able to suppress the processing of contextual information. If true, one might predict older adults to perform differently to younger adults in a task akin to that by Olson and Marshuetz (2005) that separates out the influences of making irrelevant changes to the absolute and relative spatial locations of objects – this being the aim of the present study. A description of the current

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[6] Younger adult's apparent inhibition of task-irrelevant background information contrasts somewhat with studies such as Campo et al. (2010) and Elsley and Parmentier (2015) which showed that younger adults' default position when processing object identity is to bind these objects to their location, even when location is task-irrelevant. The reason for this difference is unclear, but may lie in their use of multiple object arrays, compared the single object arrays used by Chee et al. (2006)

study along with our predictions across younger and older adult groups is presented below.

The present study

Experiment 9 aimed to assess age-related differences in object-location binding in a task based on that devised by Olson and Marshuetz (2005), modified to counter a potential confound in the original design. Specifically, Olson and Marshuetz's original study assessed task-irrelevant absolute location changes (whereby the object remained in the same corner of the smaller white square but moved in terms of its absolute location on screen), and task irrelevant location changes that occurred in both relative and absolute dimensions (whereby the object both moved to a different corner of the white square and changed its absolute location on screen). They did not, however, have a condition that would allow assessment of relative location changes in isolation. Whenever a relative change occurred, it occurred in tandem with an absolute change. Consequently, the claimed relative change in fact constituted a change in both absolute and relative object location, a fact briefly conceded by Olson and Marshuetz (2005). Accordingly, in the present study we overlap the positioning of the smaller white context squares in the centre of the larger grey square, such that the white context square (Sqr 1) can move without altering the absolute location of the object. Thus, the present experiment contains four location conditions (No change; absolute change; relative change; both change) as opposed to Olson and Marshuetz' (2005) three.

The aims of Experiment 9 were twofold: first, it aimed to examine directly the impact of making task-irrelevant changes in the absolute or relative location of an object on memory for that object. Second, it aimed to assess whether older and younger adults use spatial information in the same manner (with regard to relative and absolute location encoding).

In younger adults, changing both the relative and absolute location of objects should elicit the slowest response latencies (change both condition) relative to the no location change condition or the in the absolute location change condition, matching the conditions and pattern of performance observed by Olson and Marshuetz (2005. See also Lin & He, 2012). The relative change condition, presents two competing possibilities in terms of performance. One possibility is that a relative location change (while the absolute location remains consistent) will produce slower response latencies compared to the no change condition and compared to the absolute change condition because items are remembered in the context of their presentation, and consequently memory is disrupted whenever that context is changed between display and test. This suggests that latencies should also be slower in the relative change condition compared to the absolute change condition. Alternatively, changing both location dimensions between array and test may lead to response latencies slower than either of the single location change conditions, with the additional finding of the absolute location change condition and the relative location change condition eliciting similar response latencies. This pattern of performance would suggest that the effect observed in Olson and Marshuetz (2005) and Lin and He (2012) was a compounded effect of changing both location dimensions, and that objects are bound to locations both in terms of either their absolute location and their relative location with either able to be drawn upon when needed.

Turning our attention to the performance of older adults, this age group typically exhibit specific difficulties in the binding of objects to context. Kessels et al. (2007) demonstrated that older adult performance was specifically worse than younger adults in a task that required the binding of objects to context. This, combined with difficulties in ignoring task-irrelevant background contextual information (Chee et al, 2006; Gazzaley et al., 2008) gives rise again to two possible explanations. If they are unable to bind objects to locations effectively (as was observed in Chapter 3, Experiment 7), then older adults should produce a flat pattern of performance, whereby they remain unaffected by all changes in location as the objects have not been bound to either their relative or absolute locations. Conversely, older adults may be slower in all cases where the stimulus moves from its original location; therefore the no change condition will elicit shorter response latencies than the relative change, absolute change, and both change conditions relative to the younger adults who are seemingly better are decoupling the object from its background context (e.g., Chee et al., 2006). Such performance may indicate that older adults are simply slowed by a change in background whereby when the original image is the same in background terms (the non-change condition) response latencies are not slowed.

In sum, this experiment tests two hypotheses for each of our age groups. For younger adults; the *context-location* binding hypothesis predicts that a relative location change (while the absolute location remains consistent) will produce slower response latencies compared to the no change condition and compared to the absolute change condition, and that latencies should be slower in the relative change condition compared to the absolute change condition; The *flexible-location binding hypothesis* predicts that changing both location dimensions between array and test will elicit response latencies slower than either of the single location change conditions and that the absolute location change condition and the relative location change condition should elicit similar response latencies. For older adults; The *null-binding hypothesis* predicts that older adults will show no signs of binding objects to locations, producing equal response latencies in all conditions; the *single-image hypothesis* predicts that the no change condition should elicit the fastest responses, with any change in location eliciting longer response times due to the image (object and background) being processed as a whole and the changes therefore representing the presentation of a new image.

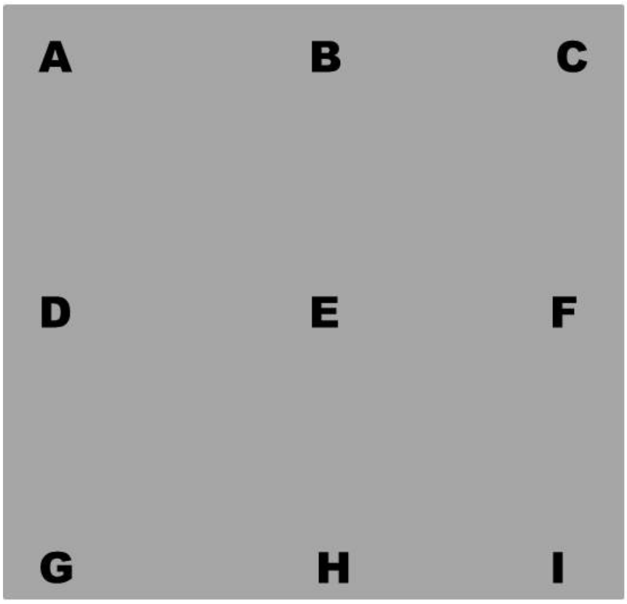
4.1.1 Method

4.1.1.1 Participants

Twenty nine younger adults (27 females, 2 males), aged 18-23 years (M = 19.72, SD = 1.87) and 15 older adults (9 females, 6 males) aged 65-82 years (M = 72.20, SD = 5.87) completed this study which lasted for approximately 30 minutes. Older adults completed the MoCA (mean score = 27.80, SD = 1.74) and using the cutoff score of 23 (Luis et al., 2009) no participants were excluded. Both younger and older adults completed the WTAR as a measure of verbal IQ (mean younger = 112.14, SD = 6.65; mean older = 122.33, SD = 3.81; $t(42)= 5.47$, $p < .001$) though note that the differences reported here see older adults outperforming younger adults, which is the opposite of the pattern of performance reported below. All participants received either course credit or an honorarium for participation.

4.1.1.2 Materials

Viewing was unconstrained at an approximate distance of 57cm at which 1cm is equal to 1° of visual angle, thus all references here to visual angle are approximate. Stimuli were 16 non-standard polygon shapes previously piloted to ensure low nameability (Chuah et al., 2004) presented as a black outline on a white background. In order to reduce variations in spatial configurations caused by shape changes between the presentation of the array and test, each stimulus sat within a 1°x1° frame (Delvenne et al., 2002). The stimulus was displayed in one of four locations within a white box (that subtended 7.5°x7.5° of visual angle) that itself appeared in one quadrant of a larger grey box subtending 14°x14° of visual angle. The four quadrants in which the white boxes appeared overlapped within the grey box such that there were 16 possible locations relative to the white boxes (one in each corner of each white box) but only 9 possible locations relative to the large grey square (see Figure 4.2). The task was purpose written using Matlab and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007).



Quadrant	Locations Encompassed
1	**A B** C **D E** F G H I
2	A **B C** D **E F** G H I
3	A B C **D E** F **G H** I
4	A B C D **E F** G **H I**

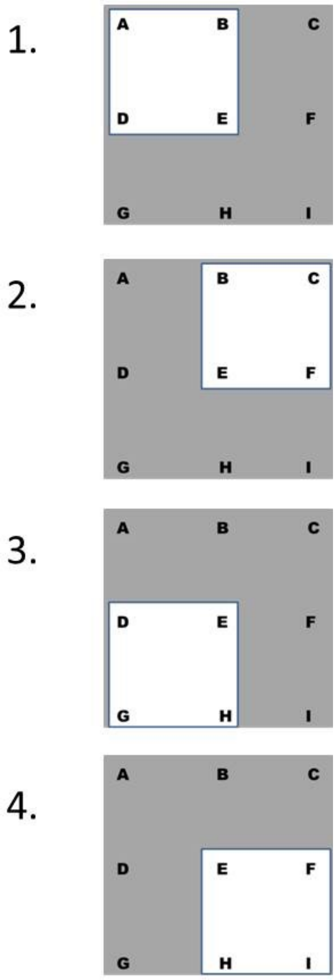


Figure 4.2. Shows the 9 absolute locations (locations described in terms of their position within the large grey square) and how each quadrant of relative locations (locations described in terms of their position within each of the four possible smaller white squares) is formed from these absolute locations. The four quadrants in which the white squares are situated overlap such that the central absolute locations are shared between multiple white squares (B,D,E,F,H).

4.1.1.3 Design

The experiment was a 2 (age group) x 4 (probe type) design with age group as a between subjects factor; and probe type as a within subjects factor. Three conditions (*no change*, *absolute change*, *both* change) directly follow Olson and Marshuetz (2005) while the remaining condition (*relative change*) is a novel feature of this experiment. Performance was measured in terms of response latencies elicited by the four experimental conditions: *no change*, *relative change*, *absolute change*, *both change* (in line with the dependent variable reported by Olson & Marshuetz, 2005), which are described in detail in the procedure section.

4.1.1.4 Procedure

Trial events and timings were as in Olson and Marzhuetz (2005) with the following exceptions: firstly, concurrent articulation was introduced in the form a two digit number between 20 and 99, randomly chosen and presented for 1000ms prior to the start of each trial. Participants were instructed to repeat the number out loud from the moment it was presented until they press a button to decide whether the object in the probe display was seen or not, at a rate of approximated three articulations per second. Compliance with the articulation instructions was monitored throughout by the experimenter. In line with previous chapters of this thesis, the shape stimuli consisted of irregular polygons (rather than regular shapes or faces) and in order to overcome the fact that relative location changes were confounded by absolute changes in location in Olson and Marhsuet's (2005) original version of the task, an extra experimental condition was devised. Consequently, the potential locations in which items could be presented was amended slightly, and can be seen in Figure 4.3. Each trial began with presentation of a random two digit number (between 20 and 99) for 1000ms which, as a means of concurrent articulation (to reduce the possibility of verbalizing the shape stimuli), participants were instructed to repeat out loud at a rate of two words per second for the duration of the trial (experimenter monitored, and maintained until a probe response was collected). A fixation cross was then shown for 507ms, immediately followed by the TBR display for 267ms. After a delay of 1600ms the probe was displayed. Participants were instructed to respond as quickly and accurately as possible in identifying whether the stimulus was the same, or different to that shown in the TBR display. Instructions included the specific statement that location was not relevant to the task (in other words, it does not matter if the shape has moved locations). The probe stimulus fell into one of four conditions. In the *no change* condition, the shape maintained its position in the white box, which also did not move. Thus the absolute and relative position of the shape was consistent between display and test. In the *relative change* condition the shape maintained its absolute position in space, but its relative position was altered by moving the white box to a new quadrant of the grey square. In the *absolute location change* condition, the shape maintained its position within the white box but the white box was moved to a new quadrant (thus the relative location was maintained, but the absolute location changed). Finally, in the both change condition the shape moved to a new position within the white box (relative location change) and the white box moved to a new quadrant permitting a change in absolute location too. See Figure 4.3 for an outline of the trial procedure and the differences in probe types.

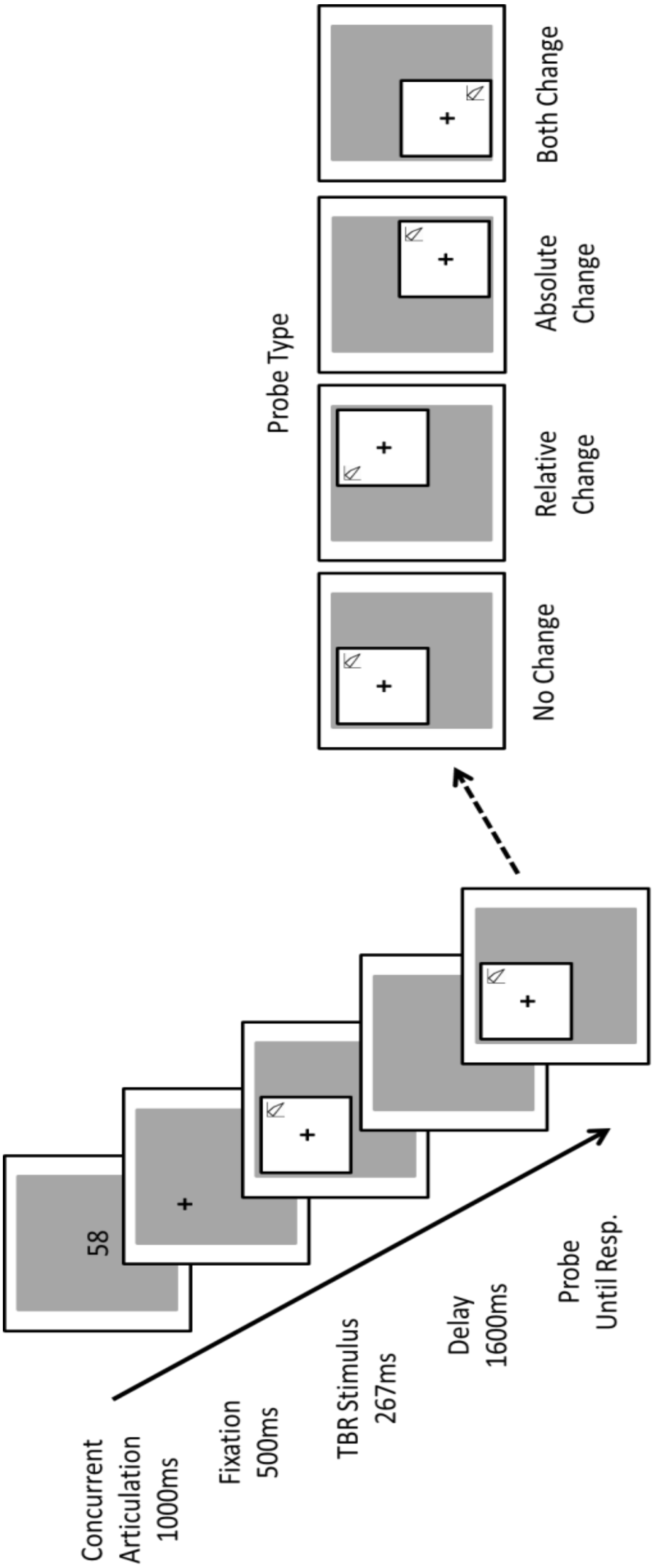


Figure 4.3. Trial procedure with examples of how location changes in each probe type relative to the TBR display

In all conditions, the identity of the shape changed on one half of all trials. Trials from each condition were randomly mixed for each participant, who responded by pressing the 'f' or 'j' keys on a standard keyboard. Key mapping was swapped for each new participant within each age group. See Figure 4.3 for trial procedure and examples of each probe type.

Each participant completed 192 trials in total; 8 practice and 184 experimental, with breaks after every 23 trials.

4.1.1.5 Data Analysis

The analysis conducted was a 2 (age group: young; older) x 4 (probe type: no change; relative change; absolute change; both change) ANOVA for repeated measures, with age as a between subjects factor. T-tests were also supplemented with their Bayesian equivalents. All analyses conducted using JASP statistical software (JASP Team, 2016).

In order to ensure all probe conditions were directly comparable, trials where the TBR stimulus was displayed in the absolute corners of the array (Figure 4.1; positions A, C, G, I) were omitted from analysis as these positions could never produce a relative change of location without also causing a change of absolute location. Consistent with Olson and Marshuetz (2005) analyses focused on response latency due to accuracy approaching ceiling in all conditions; unsurprising given that the task required participants to commit just one object to memory. The response latencies reported are mean response times for correct responses only.

4.2 Results

A 2 (age group: younger, older) x 4 (probe type: no change, relative change, absolute change, both change) mixed effects ANOVA with age as a between subjects factor indicated a main effect of age group, F (1,42) = 15.79, MSE = 138627 , p< .001, ηp^2 = .27, BF_{10} = 40.24, with younger adults (M = 873ms, SD = 197ms) faster than older adults (M = 1112ms, SD = 173ms) overall (see Figure 4.4.)

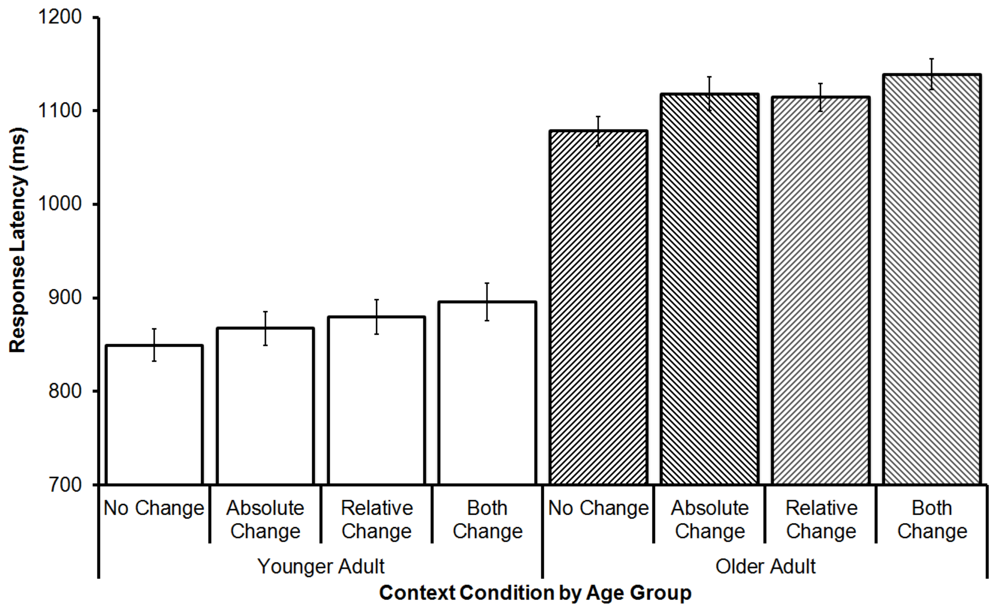


Figure 4.4. Mean response latency (milliseconds) for each probe condition as a function of age group. Error bars represent one standard error of the mean.

There further was a significant main effect of probe type, F (3,126) = 8.76, MSE = 1910, p <.001, ηp^2 = .0.17, BF_{10} = 735.70. Performance in the no change condition (M = 927ms, SD = 210ms) was faster than the relative change condition (M = 960ms, SD = 217ms; t(43) = 3.69, p < .001, d = 0.56, BF_{10} = 45.53), faster than the absolute change condition (M = 953ms, SD = 227ms; t(43) = 2.33, p = .02, d = 0.35, BF_{10} = 1.86), and faster than the both change condition (M = 979ms, SD = 232ms; t(43) = 4.28, p < .001, d = 0.65, BF_{10} = 229.95). Note though that Bayes factor does not support a difference between no-change and absolute change conditions, where the alternative is only 1.86 times more likely than the null, falling short of our preferred threshold of being 3 times more likely (Kass & Raffety, 1995). Latencies in the relative change condition were no different to the absolute change condition, t(43) = 0.78, p = .44, d = 0.12, BF_{10} = 0.22) but non-significant in being faster than both change condition (t(43) = 1.95, p = .06, d = 0.29, BF_{10} = 0.92), although Bayes factor indicates the data to be insensitive with the alternative almost as likely as the null. Finally, latencies in the absolute change condition were faster than in the both change condition (t(43) = 2.39, p = .02, d = 0.36, BF_{10} = 2.06) although again, the Bayes factors are somewhat insensitive and so do not support this difference. There was no significant interaction between factors, F(3,126) = 0.54, MSE = 1910, p = .653, ηp^2 = .01, BF_{10} = 0.54).

In summary, Experiment 9 showed a main effect of age group, with younger adults quicker to respond that older adults throughout the experiment. The main effect of probe type showed that responses were quicker for the no change condition than for all other conditions. There was no difference between absolute change, and relative change conditions, and the both change condition led to slower responses than all other conditions.

4.3 Chapter Four General Discussion

This experiment had two main aims. First, it sought to examine the extent to which objects are incidentally bound to either relative or absolute spatial location in a task when object identity only is task relevant (Olson & Marshuetz, 2005). Critically, our version of Olson and Marshuetz's (2005) paradigm addressed a potential confound in the original study that the relative location change conditions were confounded by changes in absolute location too. The second critical aim of Experiment 9 was to investigate whether older adults may differ to younger adults in the way in which they incidentally bind objects to locations. Our findings for each aim are discussed below.

The study of Olson and Marshuetz (2005; Experiments 1 & 2) found that younger adults apparently bind objects to locations in terms of nearby contextual information. Specifically, across their three conditions (no change, global change, local change) only a local change (whereby the stimulus moved relative to its nearest contextual information, i.e., a white square) was found to elicit longer response latencies.

While Experiment 9 found a difference between the absolute response latencies of younger and older adults, there was no interaction between probe type and age group. This indicates that older adults were simply slower to respond than younger adults, rather than there being a difference in the way the task is being completed by each group. There was a clear main effect of probe type with the no change condition eliciting faster response latencies than the relative change, absolute change, and both change conditions. The insensitive Bayes factor in the no change-absolute change comparison however, suggests performance that somewhat replicates Olson and Marshuetz (Experiments 1 & 2, 2005) in terms of the difference in response latency between the no change condition and each other change condition. Planned comparisons also revealed that response latencies in the relative change condition were no different to those in the absolute change condition, and marginal (but not significantly so) in being faster than those in the both change condition. This comparison again elicited insensitive Bayes factors suggesting that the relative change condition could be somewhat analogous to the both change condition. The final comparison showed that response latencies in the absolute change condition were faster than those in the both change condition, though again Bayes factors proved insensitive. Table 4.1. summarises these comparisons for easier visualisation.

Table 4.1. Summarises the comparisons between each probe type in terms of the difference between the probe type in each row relative to each column.

	Comparison Probe			
Probe type	No change	Absolute Change	Relative Change	Both Change
No change		Faster*	Faster	Faster
Absolute Change			No Difference	Faster*
Relative Change				Faster**
Both Change				

* Bayes Factor insensitive

** Bayes Factor Insensitve & p value marginal

Addressing the issue of whether location binding occurs on the basis of relative or absolute location, we propose two possible explanations for the pattern of results reported by Olson and Marshuetz (2005). Firstly, the longer response latencies in the relative change condition (in comparison to the absolute change and no change conditions), could be considered evidence that objects are bound to their location on the basis of nearby context. Indeed, this is the explanation opted for by the authors. We refer to this position as the *context-location binding hypothesis*. Alternatively, the longer response latencies in their local change condition may have occurred because the relative change condition in those experiments actually represented the compounded effect of a change in relative location and a change in absolute location (indeed, assessment of performance where changes in relative location were made while absolute location was held constant was not possible in their paradigm). This presented the possibility that objects could be flexibly bound to either absolute location or relative context (with nothing in particular being special about the position of the object relative to the frame of reference). We refer to this alternative hypothesis as the flexible-location binding hypothesis. Experiment 9 was designed to mediate between these two alternatives.

Our data suggested that any change (absolute or relative) in the location of the TBR object produces slowed response times relative to the no change condition, though critically, relative and absolute location changes produced equivalent response latencies suggesting an equally disruptive impact on object recognition in each case. That latencies were additively slower still in the both change condition supports the idea participants were able to make use of both retained absolute or relative location in the absolute change and relative change conditions, respectively. These data lend weight to the *flexible location binding hypothesis*. This pattern of performance differs from that observed by Olson and Marshuetz (2005) who reported that a relative location change elicits a longer reaction time than an absolute location change prompting the conclusion that binding to context is key in object processing. However, in that experiment, the relative change condition constituted a change in both absolute and relative object location, meaning firm conclusions were not possible based on that data. Our data suggest that participants may be able to make use of both the absolute and relative location of objects during recognition tasks – so long as one type of spatial representation is preserved between display and test, performance does not suffer too badly (relative to changing both types of spatial representation- the both change condition).

Moving specifically to the issue of binding to relative or absolute location in older adults, existing evidence suggests that adults often exhibit specific difficulties in the binding of objects to context (Kessels et al., 2007). Older adults also exhibit difficulties in narrowing selective attention and ignoring background contextual information (Chee et al, 2006; Gazzaley et al., 2008). These two lines of evidence lead to us assessing two alternative hypotheses: The *null-binding hypothesis* whereby older adults produce similar reaction times in all probe conditions because objects are not bound to their location due to a deficit in incidental location binding (e.g. Chapter 3, Experiment 7); or the *single-image hypothesis* where any change to the probe location relative to the TBR location will elicit longer response latencies. Such performance may indicate that older adults are simply slowed by a change in background relative to younger adults (perhaps by virtue of finding irrelevant background information hard to inhibit, Chee et al., 2006; Gazzaley et al., 2008) whereby when the original image is the same in background terms (the no change condition) response latencies are not slowed.

Our data indicated that older adults were slower in responding than their younger counterparts overall (as you might predict by generalized slowed response latencies with advancing age: Salthouse, 1996), but the lack of interaction between factors suggests their pattern of performance did not differ to that of younger adults. Consequently, the *flexible location binding* hypothesis would appear to describe both younger and older adult performance in solving this task. This hypothesis suggests that both younger and older adults use both relative and absolute location in determining the location of an object which is held in memory. This finding is interesting when considered in light of older adult performance in previous studies. It falls in line with performance of older adults in Chee et al. (2006) and Gazzeley et al. (2008) where older adults seemed unable to inhibit background information when it is not task relevant. Although it should be noted that Experiment 7 in Chapter 3 of this thesis suggests that this is not the case. This cross-experiment disparity could be due to differences in the array (four objects in Experiment 7 compared to a single object array in the present experiment).

4.3.1 Summary

The key finding from this experiment is that older and younger adults cannot be clearly shown to differ in the way in which they process visual objects within their locations. Both groups of participants show some evidence of binding, that is, some slowing of performance when the initial relative or absolute location of the object changes between display and test. This suggests that, even though not relevant to the task, the shapes were bound to some form of spatial representation. However, there was no particular advantage of preserving the relative vs. absolute position of the object between display and test. These findings suggest that Olson and Marshuetz (2005; see also Lin & He, 2012) may have been hasty in suggesting objects are bound to locations purely on the basis of nearby contextual features, as when absolute and relative location changes are properly separated, they yield similar response latencies. Additionally, when the TBR object's location is changed in both relative and absolute terms (as in the Olson & Marshuetz's (2005) *relative change* conditions, and the present study's *change both* condition) performance is at its poorest. Thus the flexible binding hypothesis may better characterize the performance of adults of all ages in this task.

Chapter Five. General Discussion

5. General Discussion

5.1 Thesis aims and Summary

This thesis aimed to investigate the changes that occur in feature binding ability as a function of healthy cognitive ageing. This was achieved firstly, through experiments comparing the performance of younger adults (under the age of 30 years) and older adults (over the age of 65 years) in terms of their surface feature binding ability and location binding ability when such combinations are task relevant (intentional binding), and in terms of their location binding ability, when such combinations are not required for successful completion of the task (incidental binding). Secondly, the role of attention was explored as a possible explanation of older adult performance in these tasks; and was explored through the testing of younger adults tasked with completing feature binding experiments alongside a concurrent cognitively demanding secondary task, with the results then compared to older adult performance. Specifically, this was done by contrasting two hypotheses; the *ageing-attention* hypothesis and the *ageing-context* hypothesis. The *ageing-attention* hypothesis posited that previously observed feature binding deficits in older adults (e.g. Cowan et al., 2006) may be explainable in terms of reduced attentional resources that occur as a facet of healthy ageing (Sylvain-Roy et al., 2005). Throughout the thesis, these hypotheses were investigated by contrasting the performance of older adults with that of younger adults completing the same task while completing a concurrent cognitively demanding task of counting backwards in threes. The *ageing-context* hypothesis suggested that older adult feature-binding deficits occur due to an inability to use contextual features as an organisational cue for recognition and recall; something that younger adults are habitually shown to do (Meulenbrock et al., 2012). This hypothesis was investigated by contrasting the performance of cognitively healthy older adults, with that of younger adults in three different paradigms.

By way of a summary of the thesis, Chapter 2 assessed location binding and surface-feature binding performance differences between younger and older adults (Experiments 1 & 5), in addition to the attentional requirement for surface-feature binding and location binding in younger adults (Experiments 2-4). These experiments were motivated by previous findings that older adults appear to have intact surface-feature binding ability (e.g. Allen et al., 2006) but seem to exhibit location binding deficits (e.g. Cowan et al., 2006). Chapter 2 began this investigation of feature binding and ageing by adapting the paradigm of Allen et al. (2006) to allow the testing of location as a single feature (in addition to the colour and shape single features already tested in the original paradigm); and the testing of bindings between location and colour, location and shape, and colour and shape. In full, the task required participants to remember sets of colours, shapes or locations individually and binary combinations of these features (i.e., colour-shape bindings; shape-location bindings and colour-location bindings). Each block started with instructions to remember a specific feature (colour, shape, location) or combination of features. Each single trial started with the presentation of three stimuli simultaneously displayed in distinct locations. After a brief delay, a single probe item was displayed with participants required to identify whether the probe was the same as one of the stimuli in the immediately preceding array or different. The effect of binding was investigated by comparing performance in a combined feature condition with its constituent features. The task was developed through the chapter, building to Experiments 4 and 5 where the number of changes in task irrelevant features were as balanced as possible across the conditions (e.g. in the remember shapes condition, location and colour were not task relevant and changed between array and test, while in the remember location condition, shape and colour were not task relevant and changed between array and test). This was done on the evidence of Logie et al. (2011) who showed disruption to memory performance as a result of changes in irrelevant features, particularly location. It was thought possible that these disruptions to memory performance could have influenced findings from the early experiments (1-3) in Chapter 2. In these experiments, each of the surface feature conditions (colour, shape, colour & shape) included an irrelevant change in location between array (where objects were presented in one of six possible locations) and test (where objects were always presented centrally), while each of the location conditions (location, location & colour, location & shape), saw no such differences between array and test. It was thought that as a result, Experiments 1-3 may have masked location binding issues, or attentional requirement, by artificially impairing surface feature binding performance with this irrelevant change in location. Consistent findings across all experiments in Chapter 2 however, suggest these irrelevant changes did not mask any potential issues.

Experiments 1 and 5 suggested that neither surface-feature binding nor location binding are specifically affected by healthy ageing, with older adults showing a general decline in performance across all conditions that was not specific to feature binding of any type. That location binding was not shown to be disrupted stands in contrast to numerous studies (Cowan et al., 2006, Kessels et al., 2007; Mitchell et al., 2000). Specifically, Mitchell et al. (2000) tested younger and older adults on their memory for objects, locations, and combinations of object and location presenting three objects in a serial fashion, each in a unique location with participants focusing on which ever of the memory conditions was cued at the start of the trial (object identity, location identity, object & location combination). The probe consisted only of the to-be-remembered item (the object in an unused location, a mark indicating the location, or the object in a location). Older adults were found to be specifically impaired in the location binding condition, though no different to younger adults in the other single feature conditions (colour, shape). That the experiments in Chapter 2 showed no specific location binding impairment for older adults, opposing the results of Mitchell et al. (2000), is probably best explained by the additional memory requirements of the serial presentation method adopted in Mitchell et al (2000), rather than the simultaneous presentation used in the Chapter 2 experiments. Thus, the findings in Chapter 2 do not support the ageing context hypothesis: that older adult feature-binding deficits occur due to an inability to use contextual features as an organisational cue for recall.

The *ageing-attention* hypothesis, in contrast, suggested that older adults should be impaired on any binding task that is effortful, and given previous findings showing a potential location binding deficit (e.g. Cowan et al., 2006), that older adults should show poorer performance in the location binding conditions, relative to their constituent single feature conditions (e.g. poorer performance in the colour & location condition, when compared to the single feature conditions of colour, or of location). Experiments 2-4 showed no detrimental impact of cognitive load on either surface-feature binding or location binding, matching the uniform decline in performance recorded in the older adult groups. As such the ageing-attention hypothesis cannot be rejected, although it is supported in a manner different to that initially predicted as rather than being an explanation of a specific binding deficit (where location binding was expected to be more cognitively demanding that surface-feature binding), it instead explains the pattern of a general age related decline in memory performance. These findings are again inconsistent with Cowan et al. (2006) where an age-related location binding deficit was shown and attributed to divided attention, with again the best explanation for this perhaps being the relatively simple arrays used in the experiments in Chapter 2.

In addition to findings related to ageing, Experiments 2-4 showed no evidence that either surface feature binding or location binding, as assessed by the adapted Allen et al. (2006) paradigm, are attentionally demanding processes. The finding in respect of surface feature binding was not surprising given earlier demonstrations of this null difference (Allen et al., 2006, 2012; cf Brown and Brockmole, 2010). That location binding did not appear attentionally demanding was surprising however, as it runs contrary to a number of studies (e.g. Hyun et al., 2009). The paradigm used in Chapter 2 required participants to remember just three coloured objects; in contrast Hyun et al. (2009) presented participants with arrays of 24 squares, some of which were coloured. Perhaps then, the disparate findings are driven by the contextual differences between the paradigms. The greater density of contextual information in Hyun et al.'s (2009) paradigm may require a greater degree of attention to bind objects to locations than the relatively sparse array in the adapted Allen et al. (2006) paradigm used in Chapter 2. Although findings were not at ceiling here, it is also possible that a greater degree of attention was still required, but that the additional cognitive load was not taxing enough to elicit specific behavioural differences.

A possible method of testing the notion that cognitive load may not have been taxing enough to elicit behavioural differences, would be to conduct the study again but with the addition of older adult participants. Testing older adults, with their relatively lower working memory resources, under higher cognitive load would be enlightening as the the automaticity of feature binding and would perhaps be more practicable than either adding to the complexity of the array or using a more demanding concurrent task to a study of exclusively younger adults. However, there are potential drawbacks that would need to be addressed. The primary concern would be the use of irregular shapes as in Experiments 4 and 5. These shapes proved so difficult that older adult memory performance approached chance where they were used, and as such simpler shapes would have to be used. As such, a viable future study would be to rerun the study using the task as described in Experiment 3 (with the simpler shape and colour features), but with the addition of an older adult group also tested under high and low cognitive load.

In sum, there are two key findings here; firstly, that under intentional binding instructions, older adults show no specific deficit in either surface-feature binding, or location binding ability (Experiments 1 & 5) thus rejecting the *ageing-context hypothesis*; and secondly under additional cognitive load, younger adults also show no specific deficit in either surface-feature binding, or location binding ability suggesting that both surface-feature binding and location binding draw equally on attentional resources (Experiments 2-4). Thus the process of feature-binding (irrespective of whether it is surface-feature binding, or location binding), must occur effortlessly; providing further evidence against the *ageing-attention hypothesis*.

Chapter 3 adopted an incidental binding paradigm, of the type used by Campo et al. (2010), to contrast the performance of younger and older adults in verbal-spatial binding (Experiment 6) and visual-spatial binding (Experiment 7), and finally to assess the role of attention in incidental visual-spatial binding (Experiment 8). Following the experiments of Chapter 2 showing no specific age related decline in surface-feature binding or location binding, the next step was the investigation of incidental binding in older and younger adults (binding between features that is neither required by, nor instructed in, the task). This was on the basis of a number of studies that suggest incidental binding performance may be impaired in older adults (e.g. Kensinger, Piguet, Krendl & Corkin, 2005; Naveh-Benjamin et al., 2009), particularly in respect of binding objects to context (with spatial location acting as a contextual cue: Meulenbroek et al., 2010).

Each experiment used an adaptation of the paradigm used by Campo et al. (2010), where participants were tasked with remembering a set of four visual features or a set of four locations (with the two conditions identical visually, differing only in terms of the instructions given to participants), but never the combination. Experiment 6 tested the incidental binding of letters and locations, comparing younger and older adults. On each trial participants were shown four letters from a set of eight, each displayed in a unique location from a set of eight; then after a short delay, shown a single probe letter. The key probe type comparison was between a letter shown in the same location in which it had been presented in the four letter array (an intact probe), and a letter presented in a location that had previously contained a different letter (a recombined probe); in both critical probe conditions, the letter and the location were both present in the four letter array (and so both intact and recombined probes should prompt a 'yes' response). As hinted at above, there were two memory conditions for each age group; remember the identity of letters only, or remember the locations only. It was predicted that younger adults would show the 'binding-asymmetry' established by Campo et al. (2010), whereby when letters are task relevant they are bound to their locations (indicated by poorer performance for recombined probes relative to intact probes) and when locations were task relevant participants show no evidence of binding those locations to letters (indicated by similar performance across the intact and recombined probe conditions). Predictions for older adults were based on the *ageing-context hypothesis*. As a reminder, this hypothesis proposed that older adults will not bind objects to locations, due to impaired ability to use contextual information. Given the expectation that older adults may not encode task-irrelevant information incidentally (e.g. Naveh-Benjamin et al., 2009), that they seemingly have a reduced ability to use contextual information (Kessels et al., 2007), and may instead be reliant upon pure stimulus response associations instead of using location as an organisational cue (Meulenbroek et al., 2010). Indeed, it was predicted that older adults would not show binding asymmetry, instead performing similarly in all probe conditions irrespective of which feature was task relevant.

Findings in Experiment 6 went against expectations showing an effect of probe type (with intact probes producing higher accuracy than recombined probes) that was consistent across attended features (letters and locations) and age group. As such, findings did not show either the predicted younger adult binding-asymmetry, or the flat pattern of performance with no evidence of incidental binding that was predicted for older adults. The method used closely mirrored that described by Campo et al. (2010) yet produced markedly different results for the comparable younger adult group. This proved rather difficult to explain save for accuracy almost reaching ceiling, something not seen in either Campo et al (2010) or Elsley and Parmentier (2015), which could have masked any potential differences (though again, it should be noted that the adapted paradigm in Experiment 6 used five probe types in both conditions, rather than the four used by Campo et al.). In order to address this issue, Experiment 7 took the approach of introducing more complex visual stimuli in the form of irregular polygonal shapes, with the intended impact of both bringing performance away from ceiling and of bringing this study of incidental feature binding more in line with the experiments in Chapter 2 that investigated intentional feature binding.

Experiment 7 used an identical procedure to the prior experiment, but for the introduction of shape stimuli. Predictions were also carried over from Experiment 6, with younger adults predicted to produce the binding-asymmetry with shape-location binding evident where shapes were task relevant but not with instructions to remember locations, and older adults predicted to show no evidence of shape-location binding irrespective of which feature was task relevant. The introduction of irregular shape stimuli did have the intended effect of drawing performance away from the ceiling effect observed in Experiment 6. However, the younger adults' performance again did not reflect the binding asymmetry observed by Campo et al. (2010) and Elsley and Parmentier (2015), with younger adults instead showing no difference in performance between intact and recombined probes in either the shapes or locations conditions. There was though an unanticipated binding asymmetry in the older adult group, where there was no evidence of binding between shapes and locations when shapes were task relevant, but evidence of binding was present when location was task relevant.

The performance of younger adults is again somewhat difficult to explain, particularly as it not only differs from established findings (Campo et al., 2010; Elsley & Parmentier, 2015) but also from Experiment 6. The difficulty of the shapes could have driven the lack of binding (although this is unlikely given the findings in Experiment 8; discussed later). It is also possible that binding asymmetry is a less robust and consistent finding than had previously been assumed. There are some small methodological differences to acknowledge however, particularly with Campo et al., (2010) using a response window of

1000ms, that was not implemented here due to the extended response times expected from older adults. This lack of time pressure, may have overcome any differences which would otherwise be displayed. Additionally, the use in Chapter 3 of all five possible probe types in both task relevancy conditions, compared with Campo et al.'s (2010) use of just four in each condition should be acknowledged, though how this may have led to the inconsistent findings in respect of binding asymmetry in Experiments 6-8 here, is difficult to assess. The older adult asymmetry, presenting as the opposite of that typically shown by younger adults, is an interesting finding however, and an explanation for this may lie in the claims of Read et al. (2016); that older adult feature binding ability is intact, but older adults are more easily distracted by task irrelevant feature changes indicating possible deficits in the inhibition of irrelevant information. This line of thought requires that one consider the incidental binding paradigm as a feature inhibition task, where participants must remember the task relevant feature while inhibiting the processing of the task irrelevant feature. On this basis, older adult performance begins to look similar to that found in flanker tasks by Connelly and Hasher (1993), who showed that older adults can suppress location distractors, but not identity distractors. Crucially, inhibition has been shown to be a resource demanding process (Conway & Engle, 1994; Roberts, Hager, & Heron, 1994), which left open the possibility of researching this further by repeating the experiment with younger adults with the introduction of a cognitively demanding task. If, under this higher cognitive load, younger adults were to reproduce the performance observed in older adults in Experiment 7, then we may have our explanation of older adult performance in this task. In addition, rather than a feature binding task, this paradigm adaptation would identify the paradigm developed by Campo et al. (2010) as a feature inhibition task. This formed the basis of Experiment 8.

In Experiment 8, only a group of younger adults completed the task with the procedure as in Experiment 7, but did so twice; once under the low cognitive load condition of concurrently repeating a random two digit number out loud, and once under a high cognitive load condition of concurrently counting backwards in threes from a random two digit number. The predictions for the low cognitive load condition were that participants would produce the binding asymmetry of evidence of object-location binding only where objects were task relevant, and no evidence of binding in the location condition. On the principle that the lack of binding in the locations condition is due to an effortful inhibition process for the shape features (Conway & Engle, 1994; Roberts, Hager, & Heron, 1994), under high cognitive load participants were predicted to demonstrate evidence for binding in both the locations and the shapes task.

Under low cognitive load, participants showed the predicted binding asymmetry. In the high cognitive load condition however, there was no evidence of object-location binding in either the shapes condition or the locations condition. The evidence from the high cognitive load condition presents evidence of two key points. Firstly, that incidental location binding is both obligatory and effortful, in line with Elsley and Parmentier's (2009) findings. In terms of the effects of ageing, these findings suggest that older adults are not undertaking the task in cognitively the same manner as younger adults. As outlined in Chapter 3, there is no logical explanation of how reduced attentional resources (such as those caused by a concurrent cognitively demanding task like that used here) could cause both the pattern of results shown by these younger adults, and the pattern of results shown by older adults in Experiment 7, unless they are approaching the task differently to one another.

In sum, the key conclusions of Chapter 3 are threefold; (1) the younger adult binding asymmetry reported by Campo et al. (2010) and Elsley and Parmentier (2015), may be an inconsistent finding, occurring in just one of the three experiments in this chapter (Experiment 8; though minor differences in terms of the response window must be acknowledged); (2) older adults exhibit a binding asymmetry opposite to that shown by younger adults, binding locations to shapes, but not binding shapes to locations, which may be explainable in terms of failure of inhibition (Experiment 7; though this being only a single demonstration of this pattern of results, must be investigated further before drawing firm conclusions); finally, (3) younger adult incidental binding of shapes to location is substantially reduced under additional cognitive load, suggesting that incidental location binding is attentionally demanding (Experiment 8). In summary, the difference between younger adults under high cognitive load and older adults in terms of incidental shape-location binding performance, suggests that the *ageing-attention hypothesis* does not accurately capture changes in binding performance as a function of age. The *ageing-context hypothesis* may hold true, however this is likely not the case in this paradigm if the pattern of older adult performance is a function of inhibitory failure.

The final empirical section, Chapter 4, investigated the *ageing-context* hypothesis using an adaptation of Olson and Marshuetz's (2005) incidental binding paradigm to assess whether older and younger adults address the binding tasks used in Chapter 3 in the same manner. With the mixed findings in respect of an older adult location binding deficit shown in Chapters 2 and 3, Chapter 4 investigated first the extent to which objects are (incidentally) bound to either relative or absolute spatial location in a task when object identity only was task relevant (Olson & Marshuetz, 2005). Secondly, and perhaps more crucially, Chapter 4 investigated whether older adults differ to younger adults in the way in which they incidentally bind objects to locations. Critically, the experiment in this chapter (Experiment 9) sought to improve upon the paradigm of Olson and Marshuetz (2005). They investigated how younger adults judge the location of objects in a change detection task, manipulating the (task-irrelevant) location of objects against a simple background context consisting of a small white square (Sq1) that appeared within a larger grey square (Sq2). Participants in Olson and Marshuetz (2005, Experiment 1) were tasked with remembering the identity of a single face over a short retention period; the face was presented in one corner of Sq1 which itself would appear in one of the four quadrants of Sq2. After the initial presentation of the face array there was a short delay, followed by a probe from one of three conditions: *No change*: where the probe was identical to the array; *global change*: where the face retained its location in Sq1, but Sq1 moved to a different quadrant of Sq2; and *local change*: where the face moved to a different corner of Sq1, and Sq1 moved to a different quadrant of Sq2 (a reminder of the array and probe types is shown in figure 5.1).

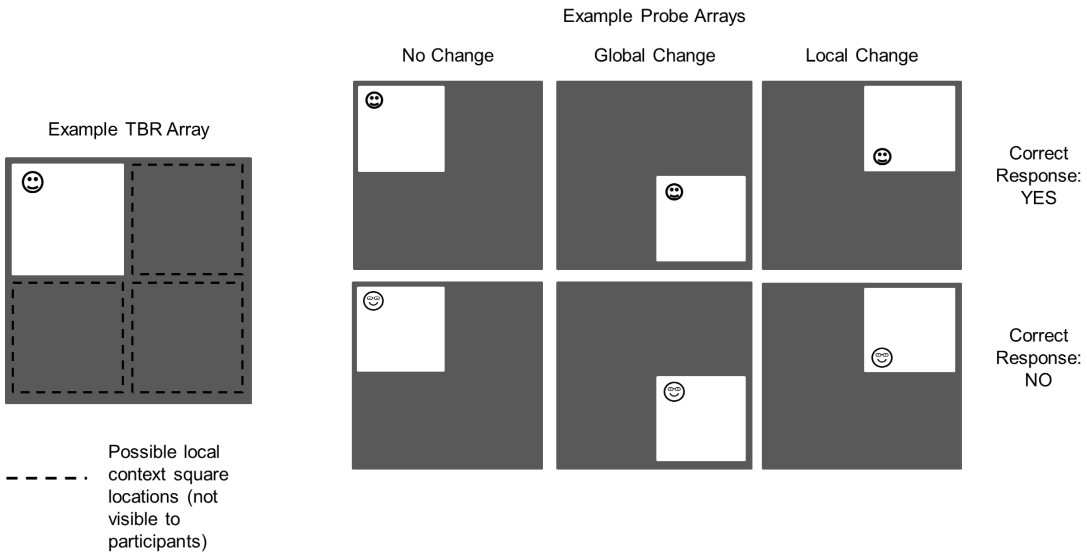


Figure 5.1. Example array and probe conditions with indications of possible Sq1 and TBR object positions (note, face stimuli were photorealistic not the simplified images indicated here). Adapted from Olson and Marshuetz (2005).

Experiment 9 sought to improve upon the paradigm used by Olson and Marshuetz (2005) by allowing the separate testing of changes in absolute location, relative location, and in changes of both dimensions concurrently. Comparing a group of younger adults with a group of older adults, in each trial the task critical object was a single abstract shape (of the type used in Experiments 4 & 5 in Chapter 2, and Experiments 7 & 8 in Chapter 3). The shape was displayed within a small white square (Sq1) that appeared within a larger grey square (Sq2) and across the experiment the (task-irrelevant) location of these objects was manipulated such that the probe object came from one of four location conditions: *No change*: where the probe was identical to the array; *absolute change*: where the shape retained its location in Sq1, but Sq1 moved to a different quadrant of Sq2; *relative change*: where Sq1 was moved, but the shape retained its location within Sq2, hence it appeared to change location within Sq1; and *both change*: where the face moved to a different corner of Sq1, and Sq1 moved to a different quadrant of Sq2. Additionally in half of the trials, the probe shape was the same as had been shown in the preceding array and in the other half of the trials the probe was different to that seen in the array.

Differences in performance between younger and older adults in Experiment 9 were limited to total differences in response latencies, with older adults slower to respond than younger adults. There was no interaction between probe type and age group indicating a fairly uniform pattern of results between younger and older adults. This lack of interaction indicates that both younger and older adults seem to complete the task in the same way. Crucially though, this was not the same pattern as had been observed by Olson and Marshuetz (2005). Separating changes into absolute and relative location (an improvement on the design of Olson and Marshuetz' paradigm) resulted in a pattern of performance that suggests both younger and older adults are able to use either relative or absolute location to equal effect in assisting in the judgment of object identity. This suggests that the flexible-location binding hypothesis, whereby participants would be able to bind objects to location in terms of both position relative to nearby contextual information, and in terms of absolute position (with only changes in both dimensions simultaneously causing difficulties in recall), may better characterise the performance of both age groups in this task.

In sum, Chapter 4 demonstrated that older adults seemingly do not differ from younger adults in their use of absolute or relative object location as a contextual cue for object recall. Both younger and older participants showed binding between the object and location, evidenced by some slowing of performance when the initial relative or absolute location of the object changes between display and test. This suggests that, even though not relevant to the task, the shapes were bound to some form of spatial representation by both younger and older adults. This further suggests that the *ageing-context hypothesis* may be incompatible with explaining older adult location binding performance. There was no evidence of a particular advantage of preserving the relative vs. absolute position of the object between display and test, standing in contrary to Olson and Marshuetz' (2005) suggestion that this should occur when the relative location is preserved.

5.2 Feature binding - Ageing, and Attentional Requirement

With the key findings from each chapter outlined above, the remainder of this chapter will seek to discuss the findings as a whole, in light of their impact for each hypothesis (ageing-attention, and ageing-context), and in terms of their place in the wider literature. This begins with a discussion of the findings relating to the role of attention in feature binding processes specifically in respect of younger adults. Following this will be a comparison of findings across chapters relating to ageing, both in respect of the role of attention in changes to feature binding ability (*ageing-attention hypothesis*), and in respect of differences in the use of contextual information that occur as a function of advanced age (*ageing-context hypothesis*).

5.2.1 Feature Binding - Younger Adult Attentional Requirement

The investigation of the role of attention in feature binding processes may not have been the primary focus of this thesis, but there are a number of interesting findings in Chapters 2 and 3 in respect of younger adult binding performance under additional cognitive load. Chapter 2 (Experiments 2-4) replicates the prior findings of Allen et al. (2006) in showing that surface feature binding was unaffected by a concurrent cognitively demanding task. Experiments 2-4 build upon these findings by additionally testing location binding ability and again show no specific deficit with a concurrent cognitively demanding task. These findings indicate that both surface-feature binding and location binding proceed in working memory by drawing no more heavily upon attentional resources than memory for individual features. Chapter 3 displays somewhat contradictory findings by indicating that for younger adults location binding is both obligatory and attentionally demanding. The low cognitive load condition in Experiment 8 replicated established findings (Campo et al., 2010; Elsley and Parmentier, 2015) by showing a 'binding asymmetry' with objects bound to locations when objects are task relevant but not when locations are task relevant. Under high cognitive load, objects were not bound to locations in either task relevancy condition, findings that support Elsley and Parmentier (2009) albeit with a subtly different paradigm.

Of course, the one comparison that cannot be made from the data in this thesis is between intentional surface-feature binding and incidental surface-feature binding due to the latter not having been tested here. As such the focus will be restricted to assessing the paradigm differences between each chapter in respect of location binding performance and the role of attention. The first difference is the set size of each experiment with the intentional binding paradigm displaying 3 objects and the incidental paradigm displaying four. As memory capacity is likely influenced by both the number of objects and the number of features within each object (Olson and Jiang, 2002) this would actually make the intentional paradigm as demanding as the incidental paradigm. The three objects displayed in Experiments 4 and 5 consist of a colour, a shape, and a location, meaning that three objects amount to nine features. In the incidental binding paradigm each object consists of two features, shape, and location, and were all displayed in the same colour (white); hence depending on whether the colour is still bound in spite of not being a useful identifying feature each array consists of eight or nine features. As such, there is ultimately no difference between the paradigms in terms of overall memory load. There are some differences in terms of presentation time (900ms in Experiments 2-4, and 2000ms in Experiment 8) though again, when one considers the differences in the arrays presented these become relatively minor. Assuming equal time is spent dwelling upon each object, Experiments 2-4 (intentional) allows 300ms per item, and Experiment 8 allows (500ms per item). The arrays in Experiment 8 are larger however and this is likely to account for any extra processing time. Additionally, it is counter intuitive to assume that an array with longer presentation time would require additional attentional resources as would be suggested by the findings in these chapters.

Intentional encoding instructions, like those in Experiments 2-4, lead to data that indicate location binding requires no attention beyond that required for remembering single features; and is that comparison to single feature memory that forms the next discussion point. Each ANOVA conducted in Experiments 2-4 compared memory for bound combinations of features, with memory for those constituent features. The notion of incidental location binding however, suggests that these single surface features would have been bound to their location irrespective of encoding instructions. Hence, under low cognitive load rather than comparing, for example, colour only, location only, and colour and location, comparisons would be made between colour and (incidentally bound) location, location only, and colour and (intentionally bound) location. Under high cognitive load, according to the findings of Experiment 8 where incidental binding is effortful, these comparisons would be between colour only, location only, and colour and location. As such the ANOVA could be compromised in such a way as to obfuscate the role of attention in location binding. Again the lack of testing in respect of incidental surface-feature binding is a drawback of this explanation, but it remains a plausible explanation given the present data and should be investigated further in order to confirm that role of attention in both surface-feature binding, and location binding.

An alternative explanation of the data in light of the difference in encoding instructions, lies in exploring so called Navon hierarchical figures (Navon, 1977). These are typically large letters constructed from smaller letters (see figure 5.1) and can be used to assess global vs local processing.

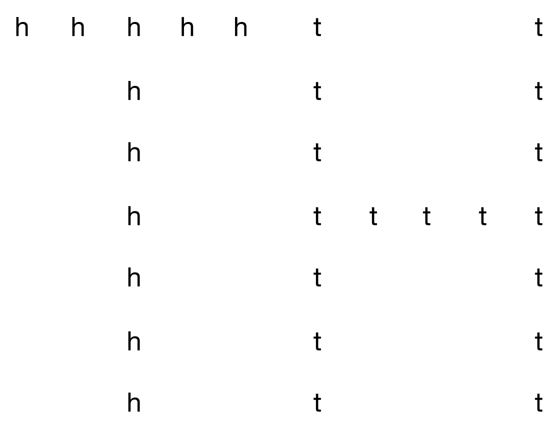


Figure 5.2. Incongruent Navon hierarchical figures, A 'T' made from 'h' and an 'H' made from 't' (Adapted from Navon, 1977).

On one level, the intentional binding instructions could be considered akin to instructing a participant to encode both the local (surface-features) and global (location) features of a stimulus. Conversely, incidental encoding instructions are more akin to instructions to just encode either the global or local features of a stimulus. Navon (1977; Experiment 3) used instructions similar to the incidental binding instructions used in Experiment 8 here, by presenting hierarchical figures and asking participants to identify them at either the global or local level. Concentrating on the global level, participants were unaffected by incongruent local letters (such as the stimuli examples in Figure 5.1); but concentrating on the local level, participant performance was poorer when faced with local letters that made an incongruent global letter. This performance is somewhat similar to the standard pattern of performance in the incidental binding study (Experiment 8; Campo et al., 2010; Elsley & Parmentier, 2015). Explicit testing of both global and local figure elements has seemingly not yet been conducted, but under the assumption that performance is similar to a binding task, one would anticipate there being little difference in performance between a condition where both global and local must be remembered in combination, compared with a condition where participants remember either global or local. This raises questions as to whether Navon hierarchical figures are in fact incidentally bound in the same manner as shapes and locations in Experiment 8.

In sum, though the thesis presents a number of interesting findings the issue of the attentional requirement of surface-feature binding, and of location binding, in younger adults remains unresolved. Future studies should seek to address the gap of incidental surface-feature binding as a start point of resolving whether all incidental binding is more cognitively demanding than memory for single features, or whether this is exclusively a facet of location binding.

5.2.2 Feature Binding - Ageing: Context and Attentional Requirement

In Chapter 2 older adults consistently showed no specific binding impairments in either surface-feature binding or location binding, instead showing a general decline in memory performance across all conditions. Much as was the case in respect of the role of attention discussed above, older adult performance in Chapter 3 was markedly different. Under incidental binding instructions older adults showed no evidence of binding objects to locations when instructed to remember shapes, but apparently did bind the two features under instruction to remember only locations (note though, that younger adults in Experiment 7 failed to replicate the expected findings of a so-called binding asymmetry).

Again, this must first be discussed in terms of differences in the paradigms presented across chapters here. While set size and presentation time can be dismissed as they were above, the difference in encoding instructions are again likely responsible for the incongruous findings between Chapter 2 and Chapter 3. With older adults not incidentally binding surface-features to locations, it stands to reason that they would still demonstrate the capacity to do so when explicit instructions to that effect are given.

Linking to the above suggestion, regarding Navon hierarchical figures (Navon, 1977) to the performance of older adults, Lux, Marshall, Thimm and Fink (2008) showed that while younger adults were quicker to identify a target letter when it was displayed at the global level, older adults were quicker to identify target letters at a local level. It should be noted though that the older adults in Lux et al. (2008) were only a mean age of 58, so younger than those tested here. As outlined above, this performance is consistent with the incidental binding tasks used in this thesis, and link to a final, albeit tentative, explanation of these data.

One final, and very tentative, suggestion for the differences between younger and older adults in respect of incidental feature binding lies in the debate between object centred and location centred attention (see Tipper, Weaver, & Wright, 1996 for a brief review). Typical younger adult performance in the Campo et al. (2010) task, such as that observed in Experiment 8, is consistent with a location centred explanation of directed attention. If one considers the features to be processed in a hierarchical fashion with the feature at the centre of attention at the top of that hierarchy, then a location centred account would produce a pattern of results whereby objects would be bound to locations only when participants are instructed to remember the objects. However, it must be accepted that performance in the high cognitive load condition of Experiment 8 is more difficult to explain in these terms. This notion would therefore suggest that older adult performance, where objects and locations were only bound when location was the instructed feature, would be explainable by an object centred attention system. Of course, this notion requires a very different theoretical approach to that taken in this thesis, and was certainly not explicitly tested here; as such it must remain a very tentative notion that may be worthy of additional study in future.

Chapters 2 and 3 indicate that differences between younger and older adult binding performance, both in terms of surface-feature binding and location binding, cannot be reasonably explained in terms of the availability of, or decline in, attentional resources. The next point of discussion must then be to compare Experiment 7, where older adults showed no evidence of incidentally binding objects to locations when focused on remembering objects, with Experiment 9, where older adults showed behavioural evidence of incidentally binding a single object with its location in a background context. These differences are best looked at in terms of the differences between the paradigms. The most obvious difference is that Experiment 7 used a memory array consisting of four objects around a central fixation, while Experiment 9 used a single object array with the critical shape displayed on a background of two squares. The differences in the memory requirement of a single object array vs a multiple object array are obvious, with Olson and Jiang (2002) clearly demonstrating that both increasing the number of objects and the number of features has a detrimental effect on memory performance. As such, Experiment 9 requiring a lower memory load could be what led to the performance differences demonstrated by the older adults in Experiments 7 and 9. This is a somewhat contentious suggestion though, given that Experiment 8 shows that the performance of younger adults under higher cognitive load does not match that of older adults in Experiment 7.

Alternatively, an explanation could lie in the differences in backgrounds between the two experiments. Experiment 7 displays its array on a plain black screen leaving any location binding likely to occur in respect of objects' position relative to one another (though not relative to the fixation cross as this has been shown to be inadequate for providing location context; Olson & Marshuetz, 2005). Experiment 9 provides participants with an explicit background of two differently coloured and sized squares as part of its array, giving participants clear reference points for location. One could perhaps characterise the array in Experiment 9 as three overlapping objects rather than a single object with a background. This would explain the contrast between Experiment 9, where older adults apparently bound single shapes to their location in relation to their background context, and Chee et al. (2005) who demonstrated that older adults do not process the bindings between an object and its background context. If the context squares in Experiment 9 were treated as additional objects rather than a background, then they would still have been processed by the older adults. However, this explanation relies on the notion that older adults process the relationships between object locations, something that was not demonstrated by the older adults in Experiment 7.

Such an explanation was favoured in respect of younger adult performance by Jiang et al. (2000). Requiring participants to remember arrays of three objects in a change detection task, Jiang et al. (2000) tested participants with probe arrays consisting of objects in identical locations to the preceding array, objects that moved but maintained their relative configuration, and objects that moved and changed their configuration (with configuration defined as objects' position relative to one another). To return to the notion that the array in Experiment 9 could be explained as three overlapping objects; This can accurately describe younger adult performance in Experiment 9 as performance is at its best when configuration at test is most similar to the preceding array (no change condition) and gets progressively poorer as the probe departs from the preceding array in respect of configuration (relative and absolute change elicit longer response latencies than the no change condition, and the both change condition elicits longer response latencies too). That older adult performance is similar to younger adults in Experiment 9 but not in Experiment 7, is not really explained by such an approach however. This explanation for younger adults hinges on the two arrays being processed in a similar manner with both arrays processed as a configuration of independent parts, rather than Experiment 9 being treated as a single object on a background. For older adults this cannot be the case, with the data clearly indicating that objects are bound to location in Experiment 9 but not Experiment 7. Thus the performance differences of older adults in Experiment 9 compared to those in Experiment 7 seems to suggest there is in fact a marked difference in the way in which these arrays are treated cognitively. Comparisons to previous literature then, suggest that differences between older adult performance in Experiments 7 and 9 are better explained by the differences in the size of the array than by the absence (Experiment 7) or presence (Experiment 9) of a visual background.

One final explanation remains. Despite the apparent lack of difference between younger and older adult performance in Experiment 9, at a behavioural level (as evidenced by the lack of interaction between probe type and age group), it is possible that differences would become apparent at a neurological level. Jost, Bryck, Vogel, and Mayr (2011) assessed the possible dissociation between age related working memory deficits, and age related inhibitory deficits. Groups of younger and older adults were assessed on their performance in a change detection task with one, three, or five objects, in which some objects were marked as irrelevant, with both behavioural and EEG measures recorded. Behavioural measures showed older adults to perform more poorly than younger adults in respect of all set sizes, with the difference between younger and older adults increasing as set size increased; a pattern of performance most simply explained as a WM deficit. However, EEG was used to record the contralateral delay (a slow negative wave sensitive to the number objects held in WM; Luria, Balaban, Awh, & Vogel, 2016) and comparisons between this measure in the single stimulus conditions, and that in the three object conditions yielded some telling findings. For younger adults, there was little difference in the timing of the contralateral delay when comparing the single stimulus condition, with the three object condition (where two of the objects would be marked irrelevant). This indicates that younger adults were effectively filtering the display to focus only on the task relevant object from the moment the display appeared on screen. Older adults however, showed a marked difference in the contralateral delay between these conditions. This was taken as evidence that in the early stages of processing the visual display, older adults are not able to filter the irrelevant stimuli, and it is this ineffective inhibition that drives the poorer behavioural performance. Moreover, estimates of the working memory capacity estimate, K, were also taken for all participants. This allowed the researchers to compare younger adults with low WM capacity, with older adults with high WM capacity, to assess whether older adults are performing the task differently to younger adults, or are instead comparable to poorer performing younger adults. The same differences outlined above in terms of inhibitory differences were again shown in this selective comparison, clearing illustrating that older adults are not undertaking the task in the same way as younger adults. As such, this experiment clearly demonstrated that behavioural evidence consistent with a WM deficit may in fact be the expression of an age related deficit in inhibitory processes.

To bring this back to the discussion of the findings of this thesis, this would mean that the findings of the adapted Allen et al. (2006) paradigm used in Chapter 2, where older adult performance mirrored that of younger adults under additional cognitive load, do not in fact contrast with the findings in Chapter 3 (Experiments 7 & 8) which suggest a deficit not explainable in terms of a WM deficit. Instead, the performance in Chapter 2 may be indicative of the same inhibitory deficit that explains the findings of Chapter 3, but would only be revealed with an intentional binding paradigm redesigned to allow the EEG assessment of a contralateral delay as found in Jost et al. (2011). Such an explanation also applies to the apparent lack of difference between younger and older adults in Chapter 4 (Experiment 9). On a single stimulus display, the behavioural differences in performance may not be great enough to show up statistically, therefore looking instead at EEG recordings to assess possible differences in inhibition, may yield findings that cannot be recorded behaviourally. Thus, replication of this study with the addition of a temporally acute neurological technique such as EEG, would seem to be a potentially fruitful avenue for future research.

5.3 Ageing-Attention Hypothesis and Ageing-Context Hypothesis- Final Summary

Starting with the *ageing-attention hypothesis*, this hypothesis is rejected. It cannot clearly be dismissed as a result of the collated findings of Chapter 2 as these three experiments simply show that younger adults experience no specific deficit in either surface-feature binding, or location binding ability under additional cognitive load, suggesting that both surface-feature binding and location binding draw equally on attentional resources. Although older adult performance in Chapter 2 matched that of younger adults under higher cognitive load suggesting that the *ageing-attention hypothesis* could yet hold true, Chapter 3 presented clear evidence against the notion of attention driven deficits in feature binding ability. Older adult performance failed to match that of younger adult performance under additional cognitive load. While older adults showed no evidence of binding shapes to locations under instructions to remember objects, they did bind these features under instructions to remember locations. Younger adults under high cognitive load, implemented to simulate the supposed reduced attentional capacity of older adults, show no evidence of object to location binding under either instructions to remember shapes, or to remember locations. This performance clearly indicates that the *ageing-attention hypothesis* cannot encompass the changes to feature binding ability that occur as a function of healthy ageing and as such, must be rejected.

The ageing-context hypothesis, may not be so easily rejected due to more mixed evidence. Chapter 2 provides clear evidence against the hypothesis with older adults showing no specific deficit in either surface-feature binding, or location binding ability. The confusion over what caused the pattern of results in Chapter 3 makes it difficult to fully reject this hypothesis. Older adults showed performance consistent both with inhibitory deficit and with a global processing bias. The *ageing-context hypothesis* could hold true, however this is likely not the case in this paradigm if the pattern of older adult performance is a function of inhibitory failure. Chapter 4 though showed that older adults seemingly do not differ from younger adults in their use of absolute or relative object location as a contextual cue for object recall. Both younger and older participants demonstrated object-location binding, evidenced by some slowing of performance when the initial relative or absolute location of the object changes between display and test. Thus the shapes were seemingly bound to some form of spatial representation by both younger and older adults further suggesting that the *ageing-context hypothesis* may be incompatible with explaining older adult location binding performance. On balance of evidence, the *ageing-context hypothesis* must be rejected.

One final point of discussion remains, the issue of how the findings presented herein relate to the role of the episodic buffer in feature binding. Experiments 1-5 continue the trend of indicating that all classes of feature binding proceed relatively effortlessly in working memory, in line with Allen et al. (2006, 2012) for example. This continues to be a challenge for the notion of the episodic buffer although there is some evidence from Experiment 8 that incidental location binding may be an effortful process (even if only in terms of an initial strategic choice) which does support the originally proposed formulation of the episodic buffer whereby it would be effortfully employed in combining features from disparate elements of working memory (e.g. a shape bound to a location).

5.4 Future Directions

In summary, this thesis indicates that older adults experience no specific deficit in feature binding ability when one's intent is guided toward remembering combinations of features (intentional feature binding). Although performance differences between younger and older adults are noted in terms of incidental location binding in a multi-probe array task, these differences do not occur as a function of the reduced attentional capacity thought to be a facet of advancing age. Older adult performance in these multi-probe array incidental binding tasks is similar in appearance to that of age related inhibitory deficits previously indicated by flanker tasks, and, as such any apparent feature-binding deficit that occurs as a function of advanced age may in fact be indicative of older adults completing incidental binding operations in a manner completely different to younger adults. Future directions for this research are noted below.

Before outlining further research suggestions, there is a methodological adjustment that would be beneficial throughout the experiments described here. Almost exclusively, the experiments described in this thesis use concurrent articulation, and where the ageing-attention hypothesis is assessed also backward counting. While the adherence to these concurrent task was monitored by the experimenter, there are benefits to recording participants' utterances. For example, these recordings can be used to check that the concurrent tasks were adhered to throughout the required period in each experiment, and the rate at which utterances are produced can be systematically measured. This measure would then allow the calculation of a simple measure to check whether participants slowed their articulation during more demanding parts of each trial, such as during encoding or retrieval. Those participants who do not adhere to the concurrent task instructions, or who strategically change their production rate can then be removed from analyses producing more consistent data. In terms of future research plans, the first, and most obvious, direction for the continuation of this research is to revisit the incidental binding paradigm utilised in Chapter 3 to investigate incidental location binding. The premise that older adults are completing the experiment as a feature inhibition task, as suggested in the discussion of Experiment 7, should be investigated using Magnetoencephalography (MEG). With Campo et al. (2010) having already conducted a similar investigation with younger adults, they should again be used to record a baseline measure, to which older adult behavioural performance and MEG recordings are compared. This would inform whether older adult performance is indeed reflective of approaching the task as a feature inhibition, rather than a feature binding, task. Similarly, the issue of binding to relative or absolute location should be replicated with the addition of MEG recordings. Although it would appear statistically that older and younger adults do not differ in terms of performance, comparisons with Experiment 7 suggest that older adults may be completing the task differently but in such a way that behavioural data appears in the same pattern for both age groups.

Magnetoencephalography would allow the investigation of this suggestion. In terms of the issues surrounding attention and incidental feature binding, the next logical step is to adapt the incidental binding paradigm used in Chapter 3, to allow the investigation of incidental surface-feature binding (perhaps in a similar manner to Ecker et al., 2016).

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Appendix

Appendix A: Experiment 6 additional analyses

Omnibus Analyses

Accuracy: A 2 (Age Group: Younger, Older) x 2 (Relevant Feature: Letter, Location) x 5 (Probe: Intact, Recombined, New Location, New Letter, New Both) repeated measures ANOVA showed no main effect of Age Group, $F(1,49) = 0.13$, $MSE = 3.90$, $p = .72$, $BF_{10} = 0.18$; a significant main effect of relevant feature, $F(1,49) = 32.13$, $MSE = 3.00$, $p < .001$, $\eta p2 = .39$, $BF_{10} = 1.80e+12$, with higher accuracy in the letter condition (M = 95.53, SD = 6.57) relative to the locations condition (M = 86.67, SD = 17.50). Additionally there was a significant main effect of probe type $F(4,196) = 3.18$, $MSE = 1.40$, $p = .02$, $\eta p2 = .06$, $BF_{10} = 0.83$ (see table A.1 for descriptive statistics and comparisons). There was no interaction between Age Group and Relevant Feature, $F(1,49) = 0.52$, $MSE = 3.00$, $p = .48$, $\eta p2 = .01$, $BF_{10} = 0.24$; there was a significant interaction between Relevant Feature and Probe type $F(4,196) = 3.20$, $MSE = 1.20$, $p = .01$, $\eta p2 = .10$, $BF_{10} = 2.38$; though the Age Group and Probe Type interaction was again non-significant $F(4,196) = 1.22$, $MSE = 1.40$, $p = .30$, $\eta p2 = .02$, $BF_{10} = 0.08$. The three-way interaction was also non-significant $F(4,196) = 0.43$, $MSE = 1.20$, $p = .79$, $\eta p2 = .01$, $BF_{10} = 0.06$.

Table A.1. Descriptive statistics, and post-hoc comparisons exploring the main effect of probe type in respect of accuracy in Experiment 6.

			Comparisons (df=50) t-statistic (BF_{10})				
Probe Type	Mean	Standard Deviation	Intact	Recombined	New Location	New Shape	New Both
Intact	93.93	5.78	-	2.65* (3.54)	3.04** (8.80)	2.42* (2.14)	0.70 (0.19)
Recombined	89.95	10.08	-	-	0.44 (0.17)	0.46 (0.17)	2.12 (1.18)
New Location	89.16	10.45	-	-	-	0.07 (0.15)	2.70** (3.94)
New Shape	89.27	13.46	-	-	-	-	1.81 (0.69)
New Both	93.19	6.07	-	-	-	-	-

*p < .05
**p < .01

Reaction Time: A similar repeated measures ANOVA showed a main effect of Age Group, F(1,49) = 11.63, MSE = 1.79e+7, p < .01, ηp2 = .19, BF_{10} = 7.85, with younger adults (M = 1094, SD = 352) responding more quickly than older adults (M = 1559, SD = 1052); there were no main effects of relevant feature, F(1,49) = 0.93, MSE = 1.39e+7, p = .34, ηp2 = .02, BF_{10} = 0.23, or of probe type F(4,196) = 0.48, MSE = 1.22e+7, p = .75, ηp2 = .01, BF_{10} = 0.01. There were no significant interactions between Age Group and Relevant Feature, F(1,49) = 0.25, MSE = 1.39e+7, p = .62, ηp2 = .01, BF_{10} = 0.17; between Relevant Feature and Probe type F(4,196) = 1.39, MSE = 1.17e+7, p = .24, ηp2 = .03, BF_{10} = 0.04; though the Age Group and Probe Type interaction was not significant F(4,196) = 0.96, MSE = 1.22e+6, p = .43, ηp2

= .02, BF_{10} = 0.04. The three-way interaction was similarly non-significant F(4,196) = 0.49, MSE = 1.17e+7, p = .74, ηp2 = .01, BF_{10} = 0.06.

Positive Probe Type Analysis

Analysis of the positive probe types (Shape: Intact, Recombined, New Location; Location: Intact, Recombined, New Shape) was also conducted.

Accuracy: A 2 (Age Group: Younger, Older) x 2 (Relevant Feature: Shape, Location) x 3 (Probe: Intact, Recombined, Alternative 'Yes') ANOVA revealed no main effect of Age Group, F(1,49) = 1.08, MSE = 3.90, p = .30, ηp2 = .02, BF_{10} = 0.30; a significant main effect of relevant feature, F(1,49) = 13.47, MSE = 3.40, p < .001, ηp2 = .22, BF_{10} = 84430.06, with higher accuracy in the letter condition (M = 94.58, SD = 7.30) relative to the locations condition (M = 86.26, SD = 19.59); and a significant main effect of probe type F(2,98) = 5.65, MSE = 1.70, p < .01, ηp2 = .10, BF_{10} = 6.56 (see table A.1 for descriptive statistics and comparisons). There were no significant interactions between Age Group and Relevant Feature, F(1,49) < 0.01, MSE = 3.40, p = .99, BF_{10} = 0.21; or Relevant Feature and Probe type F(2,98) = 2.54, MSE = 1.10, p = .08, ηp2 = .05, BF_{10} = 0.48; and no interaction between Age Group and Probe Type F(2,98) = 0.02, MSE = 1.70, p = .98, BF_{10} = 0.07. The three-way interaction was similarly non-significant F(2,98) = 0.07, MSE = 1.10, p = .94, BF_{10} = 0.21.

Reaction Time: An ANOVA as above showed a main effect of Age Group, F(1,49) = 18.26, MSE = 1.13e+7, $p < .001$, ηp2 = .27, BF_{10} = 144.135, with younger adults (M = 1018, SD = 372) producing faster responses than older adults (M = 1535, SD = 1332); no main effect of relevant feature, F(1,49) = 0.08, MSE = 660264, p = .78, BF_{10} = 0.14, and no main effect of probe type F(2,98) = 0.93, MSE = 563092, p = .40, BF_{10} = 0.04. There were non-significant interactions between Age Group and Relevant Feature, F(1,49) = 0.18, MSE = 660264, p = .67, BF_{10} = 0.21; or Relevant Feature and Probe type F(2,98) = 1.94, MSE = 498378, p = .15, ηp2 = .04, BF_{10} = 0.12; or Age Group and Probe Type F(2,98) = 1.97, MSE = 563092, p = .12, ηp2 = .04, BF_{10} = 0.37. The three-way interaction was similarly non-significant F(2,98) = 2.11, MSE = 498378, p = .13, ηp2 = .04, BF_{10} = 0.44.

Negative Probe Type Analysis

Analysis of the negative probe types (shape: New Shape, New Both; Location: New Location, New Both) was also conducted.

Accuracy: A 2 (Age Group: younger, older) x 2 (Relevant Feature: Shape, Location) x 2 (Probe: New Both, Alternative ‘No’) ANOVA showed no effect of Load, F(1,49) = 1.42, MSE = 1.40, p = .24, ηp2 = .03, BF_{10} = 0.32; a significant main effect of relevant feature, F(1,49) = 47.93, MSE = 1.10, $p < .001$, ηp2 = .48, BF_{10} = 3.71e+9, with better accuracy in the letter condition (M = 96.95, SD = 5.01) relative to the locations condition (M = 87.28, SD = 13.86) but no main effect of probe type F(1,49) = 1.55, MSE = 0.80, p = .22, ηp2 = .03, BF_{10} = 0.38. There was no interaction between Age Group and Relevant Feature, F(1,49) =

3.53, MSE = 1.10, p = .07, ηp2 = .07, BF_{10} = 1.09; there was a significant interaction of Relevant Feature and Probe type F(1,49) = 4.80, MSE = 0.90, p = .03, ηp2 = .09, BF_{10} = 2.47; but no interaction between Age Group and Probe Type F(1,49) = 0.72, MSE = 0.80, p = .40, ηp2 = .02, BF_{10} = 0.28. The three-way interaction was also non-significant F(1,49) = 0.02, MSE = 0.90, p = .90, BF_{10} = 0.27.

Reaction Time: An ANOVA as above revealed no effect of Age Group, F(1,49) = 0.26, MSE = 2.44e+7, p = .18, ηp2 = .04, BF_{10} = 0.38; no effect of relevant feature, F(1,49) = 1.04, MSE = 2.22e+8, p = .31, BF_{10} = 0.34; and no main effect of probe type F(1,49) = 0.81, MSE = 2.20e+7, p = .37, ηp2 = .02, BF_{10} = 0.30. There were no significant interactions between Age Group and Relevant Feature, F(1,49) = 0.12, MSE = 2.22e+7, p = .74, BF_{10} = 0.25; Relevant Feature and Probe type F(1,49) = 1.12, MSE = 2.22e+7, p = .30, ηp2 = .02, BF_{10} = 0.56; or of Age Group and Probe Type F(1,49) = 0.25, MSE = 2.20e+7, p = .62, ηp2 = .01, BF_{10} = 0.14. The three-way interaction was similarly non-significant F(1,49) = 0.25, MSE = 2.22e+7, p = .62, ηp2 = .01, BF_{10} = 0.34.

Appendix B: Experiment 7 additional analyses

Omnibus Analyses

Accuracy: A 2 (Age Group: Younger, Older) x 2 (Relevant Feature: Shape, Location) x 5 (Probe: Intact, Recombined, New Location, New Shape, New Both) repeated measures ANOVA showed a main effect of Age Group, $F(1,55) = 10.70$, $MSE = 589.8$, $p < .001$, $\eta p2 = .16$, $BF_{10} = 10.65$, with younger adults ($M = 78.15$, $SD = 15.18$) showing higher accuracy than older adults ($M = 71.29$, $SD = 18.07$); a significant main effect of relevant feature, $F(1,55) = 44.70$, $MSE = 317.6$, $p < .001$, $\eta p2 = .43$, $BF_{10} = 2.11e+17$), with lower accuracy in the shape condition ($M = 69.97$, $SD = 14.06$) relative to the locations condition ($M = 81.04$, $SD = 17.26$). Additionally there was a significant main effect of probe type $F(4,220) = 5.826$, $MSE = 182.8$, $p < .001$, $\eta p2 = .10$, $BF_{10} = 6.54$ (see table B.1 for descriptive statistics and comparisons). There were significant interactions between Age Group and Relevant Feature, $F(1,55) = 4.75$, $MSE = 182.8$, $p = .03$, $\eta p2 = .05$, $BF_{10} = 6.19$; and between Relevant Feature and Probe type $F(4,220) = 6.46$, $MSE = 143.2$, $p < .001$, $\eta p2 = .10$, $BF_{10} = 11.20$; though the Age Group and Probe Type did not reach significance, $F(4,220) = 2.24$, $MSE = 182.8$, $p = .07$, $\eta p2 = .04$, $BF_{10} = 0.29$. The three-way interaction was significant $F(4,220) = 2.91$, $MSE = 143.2$, $p = .02$, $\eta p2 = .05$, $BF_{10} = 0.62$, though the Bayes Factors was insensitive.

Table B.1. Descriptive statistics, and post-hoc comparisons exploring the main effect of probe type in respect of accuracy in Experiment 7.

			Comparisons (df=56) t-statistic (BF_{10})				
Probe Type	Mean	Standard Deviation	Intact	Recombined	New Location	New Shape	New Both
Intact	79.24	14.21	-	2.67* (3.49)	1.21 (0.29)	3.77** (62.32)	1.92 (0.80)
Recombined	74.90	16.39	-	-	1.09 (0.25)	2.27 (1.52)	0.10 (0.15)
New Location	76.98	16.56	-	-	-	3.40** (22.28)	1.25 (0.30)
New Shape	71.28	18.17	-	-	-	-	2.48* (2.39)
New Both	75.11	17.03	-	-	-	-	-

*p < .05
**p < .01

Reaction Time: A similar repeated measures ANOVA showed a main effect of Age Group, F(1,55) = 44.43, MSE = 1.79e+7, p < .001, ηp2 = .45, BF_{10} = 726311.24, with younger adults (M = 1158, SD = 518) responding more quickly than older adults (M = 1926, SD = 671); there were no main effects of relevant feature, F(1,55) = 3.16, MSE = 1.40e+7, p = .08, ηp2 = .07, BF_{10} = 10.23 (though Bayes Factors suggest a difference) or of probe type F(4,220) = 1.26, MSE = 160991, p = .29, ηp2 = .02, BF_{10} = 0.02. There were significant interactions between Age Group and Relevant Feature, F(1,55) = 4.28, MSE = 326795, p = .04, ηp2 = .07, BF_{10} = 5.96; and between Relevant Feature and Probe type F(4,220) = 3.48, MSE = 148235, p < .01, ηp2 = .06, BF_{10} = 0.56 (note Bayes Factors tend toward the null however); though the Age Group and Probe Type interaction was not significant F(4,220) = 1.17, MSE =

3.54e+8, $p = .33$, $\eta p2 = .02$, $BF_{10} = 0.05$. The three-way interaction was similarly non-significant $F(4,220) = 1.48$, $MSE = 149235$, $p = .21$, $\eta p2 = .03$, $BF_{10} = 0.12$.

Positive Probe Type Analysis

Analysis of the positive probe types (shape: Intact, Recombined, New Location; Location: Intact, Recombined, New Shape) was also conducted.

Accuracy: A 2 (Age Group: Younger, Older) x 2 (Relevant Feature: Shape, Location) x 3 (Probe: Intact, Recombined, Alternative 'Yes') ANOVA revealed no main effect of Age Group, $F(1,55) = 1.68$, $MSE = 573.10$, $p = .20$, $\eta p2 = .03$, $BF_{10} = 0.42$; a significant main effect of relevant feature, $F(1,55) = 6.63$, $MSE = 383.50$, $p = .01$, $\eta p2 = .10$, $BF_{10} = 987.36$), with lower accuracy in the shape condition ($M = 73.03$, $SD = 12.93$) relative to the locations condition ($M = 79.53$, $SD = 18.26$). There was though a significant main effect of probe type $F(2,110) = 5.34$, $MSE = 147.25$, $p < .01$, $\eta p2 = .09$, $BF_{10} = 1.10$ (though Bayes Factors are insensitive here). There was no significant interaction between Age Group and Relevant Feature, $F(1,55) = 2.58$, $MSE = 383.50$, $p = .11$, $\eta p2 = .04$, $BF_{10} = 2.55$; a the interaction between Relevant Feature and Probe type did not reach statistical significance, $F(2,110) = 2.89$, $MSE = 102.17$, $p = .06$, $\eta p2 = .05$, $BF_{10} = 0.17$; and no interaction between Age Group and Probe Type $F(2,110) = 0.41$, $MSE = 147.25$, $p = .67$, $\eta p2 = .01$, $BF_{10} = 0.08$. The three-way interaction was similarly non-significant, $F(2,110) = 1.74$, $MSE = 102.17$, $p = .18$, $\eta p2 = .03$, $BF_{10} = 0.18$.

Reaction Time: An ANOVA as above showed a main effect of Age Group, $F(1,55) = 37.27$, $MSE = 1.11e+7$, $p < .001$, $\eta p2 = .40$, $BF_{10} = 327303.00$, with younger adults (M = 1242, SD = 779) producing faster responses than older adults (M = 1803, SD = 721); no main effect of relevant feature, $F(1,55) = 0.06$, $MSE = 391721$, $p = .80$, $BF_{10} = 0.19$, and no main effect of probe type, $F(2,110) = 0.25$, $MSE = 182151$, $p = .78$, $BF_{10} = 0.05$. There was a significant interaction between Age Group and Relevant Feature, $F(1,55) = 4.92$, $MSE = 391721$, $p = .03$, $\eta p2 = .08$, $BF_{10} = 8.57$; but no interactions between Relevant Feature and Probe type, $F(2,110) = 2.64$, $MSE = 196096$, $p = .08$, $\eta p2 = .05$, $BF_{10} = 4.04$; or Age Group and Probe Type, $F(2,110) = 1.09$, $MSE = 182151$, $p = .34$, $\eta p2 = .02$, $BF_{10} = 1.26$. The three-way interaction was similarly non-significant, $F(2,110) = 0.04$, $MSE = 196096$, $p = .96$, $BF_{10} = 1.18$.

Negative Probe Type Analysis

Analysis of the negative probe types (shape: New Shape, New Both; Location: New Location, New Both) was also conducted.

Accuracy: A 2 (Age Group: Younger, Older) x 2 (Relevant Feature: Shape, Location) x 2 (Probe: New Both, Alternative 'No') ANOVA revealed a main effect of Age Group, $F(1,55) = 16.49$, $MSE = 465.70$, $p < 001$, $\eta p2 = .23$, $BF_{10} = 126.89$, with younger adults (M = 78.79, SD = 15.01) producing better accuracy than older adults (M = 66.87, SD = 18.44); a significant main effect of relevant feature, $F(1,55) = 84.93$, $MSE = 188.85$, $p < .001$, $\eta p2 = .60$, $BF_{10} = 1.81e+26$, with lower accuracy in the shape condition (M = 65.26, SD = 14.35) relative to the locations condition (M = 83.30, SD = 15.45) but no significant effect of probe type, $F(1,55) = 2.02$, MSE = 55.20, $p = .16$, $\eta p2 = .04$, $BF_{10} = 0.19$. There was no interaction between Age Group and Relevant Feature, $F(1,55) = 2.78$, MSE = 188.85, $p = .10$, $\eta p2 = .02$, $BF_{10} = 0.22$; there was a significant interaction of Relevant Feature and Probe type $F(1,55) = 4.10$, MSE = 46.17, $p < .05$, $\eta p2 = .06$, $BF_{10} = 0.27$ (though the Bayes Factor support the null); and no interaction between Age Group and Probe Type $F(1,55) = 0.08$, MSE = 55.20, $p = .79$, $BF_{10} = 0.21$. The three-way interaction was though, significant, $F(1,55) = 10.64$, MSE = 46.17, $p < .01$, $\eta p2 = .15$, $BF_{10} = 2.23$.

Reaction Time: An ANOVA as above revealed a main effect of Age Group, $F(1,55) = 44.34$, MSE = 4.93e+7, $p < .001$, $\eta p2 = .45$, $BF_{10} = 582024.87$, with younger adults (M = 1161, SD = 367) producing faster responses than older adults (M = 2009, SD = 714); a significant main effect of relevant feature, $F(1,55) = 21.06$, MSE = 95143, $p < .001$, $BF_{10} = 76769$, with responses in the shapes condition (M = 1587, SD = 676) slower than in the locations condition (M = 1390, SD = 651); though no main effect of probe type, $F(1,55) = 1.90$, MSE = 40804, $p = .17$, $\eta p2 = .03$, $BF_{10} = 0.22$. There were no significant interactions between Age Group and Relevant Feature, $F(1,55) = 0.30$, MSE = 95143, $p = .59$, $BF_{10} = 0.23$; Relevant Feature and Probe type, $F(1,55) = 0.35$, MSE = 89549, $p = .56$, $\eta p2 = .01$, $BF_{10} = 0.20$; or of Age Group and Probe Type $F(1,55) = 1.12$, MSE = 40804, $p = .30$, $\eta p2 = .02$, $BF_{10} = 0.25$. The three-way interaction was similarly non-significant, $F(1,55) = 0.41$, MSE = 89549, $p = .53$, $\eta p2 = .01$, $BF_{10} = 0.28$.

Appendix C: Experiment 8 additional analyses

Omnibus Analyses

Accuracy: A 2 (Load: Low, High) x 2 (Relevant Feature: Shape, Location) x 5 (Probe: Intact, Recombined, New Location, New Shape, New Both) repeated measures ANOVA showed a main effect of Load, $F(1,24) = 43.62$, $MSE = 4.60$, $p < 001$, $\eta p2 = .65$, $BF_{10} = 1.68e+14$, with performance in the low load condition (M = 79.22, SD = 18.14) producing better accuracy than the high load condition (M = 66.58, SD = 18.14); a significant main effect of relevant feature, $F(1,24) = 59.86$, $MSE = 1.80$, $p < .001$, $\eta p2 = .71$, BF_{10} =2.90e+7, with lower accuracy in the shape condition (M = 68.20, SD = 18.90) relative to the locations condition (M = 77.54, SD = 18.39). Additionally there was a significant main effect of probe type, $F(4,96) = 4.71$, $MSE = 4.50$, $p = .002$, $\eta p2 = .16$, BF_{10} = 647.12 (see table C.1 for descriptive statistics and comparisons). There were significant interactions between Load and Relevant Feature, $F(1,24) = 30.02$, $MSE = 1.90$, $p < .001$, $\eta p2 = .56$, BF_{10} = 1.32E+04; and an interaction of Relevant Feature and Probe type $F(4,96) = 2.57$, $MSE = 0.90$, $p = .04$, $\eta p2 = .10$, BF_{10} = 0.05 (however the Bayes Factor here supports the null); though the Load and Probe Type interaction was not significant, $F(4,96) = 0.48$, $MSE = 2.50$, $p = .75$, $\eta p2 = .02$, BF_{10} = 0.02. The three-way interaction was significant $F(4,96) = 8.73$, $MSE = 0.80$, $p < .001$, $\eta p2 = .27$, BF_{10} = 3.10.

Table C.1. Descriptive statistics, and post-hoc comparisons exploring the main effect of probe type in respect of accuracy in Experiment 8.

			Comparisons (df=24) t-statistic (BF_{10})				
Probe Type	Mean	Standard Deviation	Intact	Recombined	New Location	New Shape	New Both
Intact	73.33	19.78	-	2.37* (2.15)	1.89 (0.97)	0.29 (0.22)	1.90 (0.99)
Recombined	68.83	20.86	-	-	0.31 (0.22)	0.85 (0.29)	3.04** (7.79)
New Location	69.54	20.47	-	-	-	0.87** (0.30)	3.91** (49.90)
New Shape	72.17	17.31	-	-	-	-	6.57** (20863.66)
New Both	80.49	15.04	-	-	-	-	-

*p < .05
**p < .01

Reaction Time: A similar repeated measures ANOVA showed a main effect of Load, F(1,24) = 8.71, MSE = 249525, p = 001, ηp2 = .27, BF_{10} = 2.12e+8, with performance in the low load condition (M = 995.72, SD = 264.51) eliciting faster responses than the high load condition (M = 1127.58, SD = 361.86); and no significant main effect of relevant feature, F(1,24) = 2.54, MSE = 183561, p = .12, ηp2 = .10, BF_{10} = 5.12, though the Bayes Factors suggest that there is indeed a difference with shorter reaction times in the locations condition (M = 1031.11, SD = 348.93) than in the shapes condition (M = 1092.19, SD = 293.28). There was though a significant main effect of probe type F(4,96) = 3.38, MSE = 40366, p = .01, ηp2 = .12, BF_{10} = 0.22 (note that the Bayes Factor clearly indicates no such effect however; see table C.2 for descriptive statistics and comparisons). The Load and Relevant Feature interaction was not significant, $F(1,24) = 3.61$, $MSE = 89569$, $p = .07$, $\eta p2 = .13$, $BF_{10} = 2.57$; similarly so for the Relevant Feature and Probe type interaction $F(4,96) = 0.61$, $MSE = 18925$, $p = .66$, $\eta p2 = .03$, $BF_{10} = 0.29$; though the Load and Probe Type interaction was significant, $F(4,96) = 3.03$, $MSE = 35827$, $p = .02$, $\eta p2 = .11$, $BF_{10} = 0.01$ (note again though that the Bayes Factor very strongly indicates otherwise). The three-way interaction was not significant $F(4,96) = 0.21$, $MSE = 17389$, $p = .94$, $\eta p2 = .01$, $BF_{10} = 0.04$.

Table C.2. Descriptive statistics, and post-hoc comparisons exploring the main effect of probe type in respect of response latency in Experiment 8.

			Comparisons (df=24) t-statistic (BF_{10})				
Probe Type	Mean	Standard Deviation	Intact	Recombined	New Location	New Shape	New Both
Intact	1021	296	-	1.76 (0.80)	0.35 (0.22)	2.91** (5.97)	2.34* (2.03)
Recombined	1057	333	-	-	1.13 (0.38)	2.11* (1.38)	1.24 (0.42)
New Location	1030	268	-	-	-	2.04 (1.24)	2.86** (5.35)
New Shape	1102	395	-	-	-	-	0.18 (0.21)
New Both	1096	308	-	-	-	-	-

*p < .05
**p < .01

Positive Probe Type Analysis

Analysis of the positive probe types (shape: Intact, Recombined, New Location; Location: Intact, Recombined, New Shape) was also conducted.

Accuracy: A 2 (Load: Low, High) x 2 (Relevant Feature: Shape, Location) x 3 (Probe: Intact, Recombined, Alternative 'Yes') ANOVA revealed a main effect of Load, F(1,24) = 28.55, MSE = 3.60, p < 001, ηp2 = .54, BF_{10} = 1.53e+8, with performance in the low load condition (M = 76.28, SD = 19.88) producing better accuracy than the high load condition (M = 64.63, SD = 18.52); a significant main effect of relevant feature, F(1,24) = 22.41, MSE = 3.30, p < .001, ηp2 = .48, BF_{10} = 63292.29), with lower accuracy in the shape condition (M = 65.51, SD = 20.00) relative to the locations condition (M = 75.41, SD = 18.90). There was no significant main effect of probe type, F(2,48) = 2.49, MSE = 2.50, p = .09, ηp2 = .09, BF_{10} = 0.27. There was a significant interaction between Load and Relevant Feature, F(1,24) = 39.14, MSE = 1.50, p < .001, ηp2 = .62, BF_{10} = 1.39E+05; but no interaction of Relevant Feature and Probe type F(2,48) = 1.36, MSE = 0.90, p = .26, ηp2 = .05, BF_{10} = 0.11; or of Load and Probe Type F(2,48) = 0.14, MSE = 2.10, p = .87, ηp2 = .01, BF_{10} = 0.08. The three-way interaction was similarly non-significant, F(2,48) = 1.09, MSE = 1.03, p = .35, ηp2 = .04, BF_{10} = 0.19.

Reaction Time: An ANOVA as above revealed a main effect of Load, F(1,24) = 8.28, MSE = 192431, p < 01, ηp2 = .26, BF_{10} = 197982.78, with performance in the low load condition (M =995, SD = 260) producing faster responses than the high load condition (M = 1119, SD = 341); no main effect of relevant feature, F(1,24) = 0.01, MSE = 158220, p = .92, BF_{10} = 0.13, and no main effect of probe type F(2,48) = 1.43, MSE = 24466, p = .25, ηp2 = .06, BF_{10} = 0.06. There were no significant interactions between Load and Relevant Feature, F(1,24) = 2.93, MSE = 80719, p = .10, ηp2 = .11, BF_{10} = 1.48; Relevant Feature and Probe type F(2,48) = 0.90, MSE = 16058, p = .41, ηp2 = .04, BF_{10} = 0.09; or of Load and Probe Type F(2,48) = 0.21, MSE = 17647, p = .82, ηp2 = .01, BF_{10} = 0.07. The three-way interaction was similarly non-significant, F(2,48) = 0.34, MSE = 10186, p = .71, ηp2 = .01, BF_{10} = 0.12.

Negative Probe Type Analysis

Analysis of the negative probe types (shape: New Shape, New Both; Location: New Location, New Both) was also conducted.

Accuracy: A 2 (Load: Low, High) x 2 (Relevant Feature: Shape, Location) x 2 (Probe: New Both, Alternative 'No') ANOVA revealed a main effect of Load, F(1,24) = 37.33, MSE = 2.70, p < 001, ηp2 = .61, BF_{10} = 4.72e+8, with performance in the low load condition (M = 80.62, SD = 14.16) producing better accuracy than the high load condition (M = 69.38, SD = 17.25); a significant main effect of relevant feature, F(1,24) = 11.61, MSE = 3.10, p < .01, ηp2 = .33, BF_{10} = 97.40, with lower accuracy in the shape condition (M = 72.25, SD = 16.38) relative to the locations condition (M = 80.75, SD = 17.20) and additionally a significant main effect of probe type, F(1,24) = 36.51, MSE = 0.90, p < .001, ηp2 = .60, BF_{10} = 3.84, with performance in the alternative 'no' condition (M = 72.51, SD = 18.77) less accurate than in the New Both condition (M = 80.49, SD =

15.04). There was no interaction between Load and Relevant Feature, $F(1,24) = 2.52$, $MSE = 2.50$, $p = .13$, $\eta p2 = .10$, $BF_{10} = 0.92$; there was a significant interaction of Relevant Feature and Probe type $F(1,24) = 5.36$, $MSE = 0.90$, $p = .03$, $\eta p2 = .18$, $BF_{10} = 3.35$; and of Load and Probe Type $F(1,24) = 6.07$, $MSE = 1.30$, $p = .02$, $\eta p2 = .20$, $BF_{10} = 0.31$ (though the Bayes Factor indicates the opposite). The three-way interaction was also significant, $F(1,24) = 8.14$, $MSE = 1.50$, $p < .01$, $\eta p2 = .25$, $BF_{10} = 84.40$.

Reaction Time: An ANOVA as above revealed a main effect of Load, $F(1,24) = 5.77$, $MSE = 106613$, $p < .01$, $\eta p2 = .19$, $BF_{10} = 58.48$, with performance in the low load condition ($M = 1035$, $SD = 307$) leading to faster responses than the high load condition ($M = 1145$, $SD = 314$); a significant main effect of relevant feature, $F(1,24) = 9.60$, $MSE = 110517$, $p < .01$, $BF_{10} = 5915.89$, with responses in the shapes condition ($M = 1163$, $SD = 333$) slower than in the locations condition ($M = 1017$, $SD = 278$); though no main effect of probe type $F(1,24) = 0.52$, $MSE = 14697$, $p = .48$, $\eta p2 = .02$, $BF_{10} = 0.16$. There were no significant interactions between Load and Relevant Feature, $F(1,24) = 3.23$, $MSE = 28659$, $p = .09$, $\eta p2 = .12$, $BF_{10} = 0.58$; Relevant Feature and Probe type, $F(1,24) = 0.66$, $MSE = 12778$, $p = .43$, $\eta p2 = .03$, $BF_{10} = 0.23$; or of Load and Probe Type, $F(1,24) = 0.40$, $MSE = 247269$, $p = .54$, $\eta p2 = .02$, $BF_{10} = 0.21$. The three-way interaction was similarly non-significant $F(1,24) = 0.02$, $MSE = 9961$, $p = .89$, $BF_{10} = 0.28$.