BINDING OF VISUAL FEATURES IN HUMAN PERCEPTION AND MEMORY

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Dedicated to my parents

DECLARATION

I declare that this thesis is my own composition, and that the material contained in it describes my own work. It has not been submitted for any other degree or professional qualification. All quotations have been distinguished by quotation marks and the sources of information acknowledged.

Snehlata Jaswal
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Adamant queries are a hazy recollection
Remnants are clarity, insight, appreciation
A deep admiration, love, infinite gratitude
For revered Bob, John, and Jim

One a cherished guide, ideal teacher
The other a personal idol, surrogate mother
Both inspiring, lovingly instilled certitude
Jagat Sir and Ritu Ma'am

A sister sought new worlds to conquer
A daughter left, enticed by enchanter
Yet showered me with blessings multitude
My family, Mum and Dad

So many more, whispers the breeze
Without whom, this would not be
Mere mention is an inane platitude
For treasured friends forever

CONTENTS

ABSTRACT

The *leit motif* of this thesis is that binding of visual features is a process that begins with input of stimulation and ends with the emergence of an object in working memory so that it can be further manipulated for higher cognitive processes. The primary focus was on the binding process from 0 to 2500 ms, with stimuli defined by location, colour, and shape. The initial experiments explored the relative role of top-down and bottom-up factors. Task relevance was compared by asking participants to detect swaps in bindings of two features whilst the third was either unchanged, or made irrelevant by randomization from study to test, in a change detection task. The experiments also studied the differences among the three defining features across experiments where each feature was randomized, whilst the binding between the other two was tested. Results showed that though features were processed to different time scales, they were treated in the same way by Visual Working Memory processes. Relevant features were consolidated and irrelevant features were inhibited. Later experiments confirmed that consolidation was aided by iconic memory and the inhibitory process was primarily a post-perceptual active inhibition.

LIST OF FIGURES

LIST OF ABBREVIATIONS

In reverse alphabetical order:

WM	Working Memory
VWM	Visual Working Memory
VSTM	Visual Short Term Memory
TMS	Transcranial Magnetic Stimulation
STM	Short Term Memory
SPCN	Sustained Posterior Contralateral Negativity
SOA	Stimulus Onset Asynchrony
SIMPLE	Scale Invariant Memory and Perceptual Learning
SEM	Start-End Model
RT	Response Time
RSVP	Rapid Serial Visual Processing
PPC	Posterior Parietal Cortex
OSCAR	Oscillator based Associative Recall
N2pc	Negativity at posterior electrodes contralateral to the stimulus
MEG	Magneto Encephalography
LTM	Long Term Memory
fMRI	Functional Magnetic Resonance Imaging
FACADE	Form And Colour And Depth Model of Visual Processing
ERP	Event Related Potential
EEG	Electroencephalogram
CSTM	Conceptual Short Term Memory
C-SOB	Computerized Serial Order in a Box
CDA	Contralateral Delayed Activity
ANOVA	Analysis of Variance

NOTES

Throughout this work:

- The term VSTM refers to one part of VWM. VSTM is conceptualised as an intermediate visual memory store that receives input from basic perceptual processes, and from which material may be transferred out for further processing (for example to the LTM). In contrast, VWM denotes a larger complex of stores as well as processes, which enable continuous ‘online’ manipulation of information.

- The terms ‘dimensions’ and ‘features’ are used interchangeably, though it is accepted that precisely speaking, dimensions refers to colour, size, shape, location etc. whereas features are particular values on these dimensions such as red, big, square, top etc. Since features express specific values on dimensions, they are conceptually subordinate to dimensions. A change in dimensions would always mean a change in features, though the reverse may not be true and feature values may change within a dimension.

- The research assumes the refresh rate of the monitor to be 0, and consequently the study-test intervals are labelled to start from 0 ms.

CHAPTER 1

INTRODUCTION

Binding is the process whereby distinct bits of information, usually represented in different areas of the brain, are brought together for the integrated control of behaviour. It has been postulated as being basic to a host of cognitive functions, such as, parallel processing of different objects or their elements (Von der Malsburg, 1981), production of language (Fodor & Pylyshyn, 1988), consciousness (Crick & Koch, 1990), formation of the phenomenal self (Metzinger, 1995), establishment of subjective time frames (Poppel, 1997), memory and reasoning (Halford, Cowan, & Andrews, 2007), etc. These ideas however, assume a very broad conceptualization of the term 'binding'. In a more restricted way, the term denotes 'feature binding', the process whereby different features such as shape, colour, size, orientation, location, etc. are linked together to form a coherent representation of the object. It is in this sense that binding is a ubiquitous physiological sequence and an essential phase in information processing, for it provides the basis of mental representations, which in turn, are prerequisites for all cognitive processes.

It is important to realize though, that binding is not an isolated process; it always occurs in a context. There are myriad stimuli impinging on our senses at all times, vying to gain entry into our consciousness. Further, not only does sensory input emanate from a complex, dynamic environment, but it also enters a neural system that is already activated by previous inputs and is oriented towards future goals. Which aspects of the momentary sensory input are selected for further processing depends as much on the state of the system as it does on the sensory input itself.

Indeed, the fundamental questions one may ask about binding are whether, why, and how, some features are selected for binding at the cost of others. The answers to these questions presumably lie in the analysis of the whole information processing sequence from when the input from the external world is received, to when the output in the form of behaviour is given. The bottom-up view of information processing is that the input received by the brain is processed in a largely automatic way to the higher centres in the brain. Thus, *stimulus* factors primarily determine the patterns and objects that are encoded for further processing. Feature binding is viewed as an automatic, pre-attentive, transient process that arises from low level neural dynamics. The physiological basis of binding is postulated to be either conjunctively coded neurons (Baars, 1988; Deheane & Changeux, 2004; Fodor & Pylyshyn, 1988), or synchrony among participating neural networks to encode features and out of phase neural activity to encode separate objects (Singer & Gray, 1995; Von der Malsburg, 1981).

In contrast, the top-down view of information processing contends that *concepts* such as task set, instructions, and goals, determine which features and objects are selected for processing. Binding is thus thought to be more influenced by the mechanism of selective attention that dictates which features and objects are processed further. The top-down processing signals essentially emanate from Working Memory and operate in the context demarcated by it (Duncan, 2006). The reentrant processes in the brain are emphasised as the physiological basis of binding (Di Lollo, Enns, & Rensink, 2000; Hochstein & Ahissar, 2002; Lamme & Roelfsema, 2000). These imply downward and lateral feedback to the lower areas of the brain, emanating from the higher centres of the brain.

The relative influence of stimulus driven and conceptually driven processing can arguably be best studied by analyzing the processes that operate when incoming sensations are encoded in the visual system and organised as objects for further processing. The maximum interplay between bottom-up and top-down processes happens at the interface of perception and memory, and so the scope of this research is limited to binding at the threshold where the multidimensional representation of a stimulus is transformed and consolidated into an integrated object. This threshold is functionally defined rather than temporally delimited. Perceptual representation is often enough conceived as feature integration, but how a percept enters into memory and what are the processes and factors in this transfer, is the objective of this study.

Towards this purpose, the concept of binding, which inevitably involves the underlying physiological mechanisms that play a role in binding, is considered first in Chapter 2. Thereafter, the processes and stores in information processing which affect the process of binding are examined, delineating the debates which raise the interesting research questions and suggest possible hypotheses which are addressed in this thesis. Chapter 3 is an exposition of the general method and procedure adopted to test these hypotheses. The experiments are described next in Chapters 4-8, and the final Chapters 9 and 10 present a general discussion of the major findings, the limitations of this work, and the implications for future research in this area.

CHAPTER 2

A REVIEW OF LITERATURE

THE CONCEPT OF BINDING

Binding is the process whereby separate entities are linked together to form a unified, coherent representation of the world around us. Feature binding refers to linking various characteristics of the stimulus to form a coherent representation of the stimulus. It brings together rather different aspects of an object such as its shape, colour, size, orientation, location, movement, etc. Cognitive scientists postulate binding to be one of the basic processes in all information processing ranging from object identification to consciousness (Crick & Koch, 1990, but see Crick & Koch, 2003; Singer & Gray, 1995, Zimmer, Mecklinger, & Lindenberger, 2006).

The reality that is perceived is contingent upon information of diverse kinds located in many different areas of the brain. The binding problem exists because information about the features of every object in the external world goes to disparate areas of the brain. Empirical science focuses on how a person solves the binding problem at the neural as well as the behavioural level, and postulates mechanisms whereby the brain brings together information that goes to disparate areas of the brain. The modularity of the brain for processing different kinds of information is long established. Usually, however, we transcend these disparities, and accurately and effortlessly bind this myriad information to constitute a whole. So what is the underlying brain process, which binds together information that goes to distinct areas of the brain? Almost all researchers assume that the answer lies in the identification of specialised neurons or networks that participate in the same cognitive process at the same time.

When Nobel prize winners Hubel and Wiesel provided evidence for conjunctively coding cells in the striate cortex of cats (Hubel & Wiesel, 1959; 1962), and monkeys (Hubel & Wiesel, 1968), it seemed clear that specialised neurons existed to code the different objects that are encountered in the environment. Researchers soon proposed that specialised cells attuned to specific conjunctions of features are responsible for binding, and that these cells come together in a workspace that enables the flexibility of binding and unbinding, and further processing. Fodor and Pylyshyn (1988) distinguished between vertical ‘modular faculties’ and a distinct ‘central horizontal system’ capable of sharing information across modules. Baars (1988) distinguished between a vast array of unconscious, specialised, parallel processors, and a single, limited capacity, serial workspace that allows exchange of information. Deheane and Changeux (2004) proposed the ‘neuronal workspace hypothesis’, which distinguishes two computational spaces in the brain, each characterised by a distinct pattern of connectivity. They proposed a network of ‘specialised processors’, attuned to particular types of information, but sharing the characteristics of specialisation, automaticity, and fast feed forward processing, as well as ‘cortical workspace neurons’ that break the modularity of the cortex because they are able to send and receive projections to many distant areas through long range excitatory neurons. However, the idea of binding due to specialised neurons had a problem with sheer numbers. The quandary was how to grapple with the numerous stimuli, account for transience of binding, and at the same time limit the huge number of conjunctively coding neurons required for all the binding operations.

Synchrony was proposed as the alternative physiological explanation for binding. It was Von der Malsburg (1981) who first contended that a complex environment requires parallel processing of information related to different objects or events, and posited neural synchrony as the mechanism whereby such information is bound together. Singer and Gray (1995) suggested that binding is explained by transient and precise synchronisation of neuronal discharges, discovered in their laboratory by Gray, Engel, Konig, and Singer (1992) in the cat striate cortex. Indeed, synchronization was later reported in species ranging from locusts (MacLeod, Backer, & Laurent, 1998), to cats and monkeys (Gray, 1999), and of course, in humans (Singer, 1999). The idea of synchrony assumes that binding occurs throughout the brain, synchronous firing of cortical neurons leading to binding of features. The proposal faces two problems. The first is regarding how two (or more) bound objects are differentiated. Though oscillation between out of phase firing has been proposed as a possible mechanism to encode separate objects, it is rather difficult to imagine how such a precise timing mechanism is implemented, considering that there are always multiple objects in the external world, and in addition to that, the brain itself is a highly noisy environment. The second problem is related to the implication that binding is transient, because the same neurons encode all binding operations. The problem is how to account for permanence of representations after the stimulus is no longer there. Synchrony seems to be an adequate explanation of binding, only for a single object, and that too only when it is present as a percept.

Nevertheless, physiological evidence exists for specialised processors as well as synchrony, and is hard to refute. Thus, many researchers tried to resolve the dispute between synchrony and specialised neurons by proposing different kinds of bindings, but in the process merely ended up reiterating the debate. Crick and Koch (1990) differentiated at least three kinds of bindings. First, bindings 'hardwired' by genes or the experience of distant ancestors that presumably determine the response to natural stimuli. Second, bindings learnt due to experience such as those required for recognising familiar faces, or the letters of the alphabet; and third, transient bindings of novel stimuli, which require focal attention. These are presumably based on neural synchrony, and if the stimulus is repeated often enough, develop into the second kind of bindings. Baddeley (2007) mentioned two types of bindings, passive binding, contingent on automatic processes; and active binding, which requires attention. The examples used suggest that while the former refers to binding elements of the natural world for which humans are 'prepared' in an evolutionary sense, the latter type refers to binding of arbitrary, learnt elements. He further adds that long term episodic memory provides a third source of binding. Clearly, these ideas are similar to the tripartite distinction by Crick and Koch (1990). VanRullen (2009) also distinguishes between hardwired binding of natural / frequently encountered objects, and on-demand binding of meaningless / arbitrary feature conjunctions, asserting that while the latter always requires attention, the former requires attention only if there is competition by multiple objects, thus emphasizing the inhibitory function of attention. Hommel and Colzato (2009) similarly hold that binding can take place through neural synchronization of all features present at a time, or because a stored detector exists for real/familiar objects. They too, admit the possibility of both processes acting together.

Despite this measure of acceptance, there is a sense that mere perceptual integration of features, whether by synchrony or by specialised neurons, does not even begin to capture the connotation of bindings as coherent objects that are fundamental for further information processing. The object cannot be defined only as a bundle of features. At the very least the features need to be integrated so that the object can be distinguished from other objects. This implies manipulation of the basic information supplied by separate features. At the physiological level, this is probably done by the reentrant processes in the brain. These are the downward and lateral connections that feedback information to lower levels in the brain. As in any good communication system, the brain too relies on feedback mechanisms. In the visual system, for example, the lower level neurons in Area V1 send signals for forward processing, but it is also true that all higher visual centres have reentrant (downward) connections with Area V1. An important characteristic of reentrant connections is that they not only feedback to the original neurons, but also ‘receive’ signals back from them. Communication between brain areas is therefore a continuous process.

Thus, the dichotomy between synchrony and specialised neurons is currently transcended by proposals that ascribe paramount importance to the evidence of reentrant processes in the brain. These top-down processes are inevitably linked to higher cognitive functions. Edelman (1978) first proposed that reentrant signalling might be important in integrating disparate cortical areas and higher brain functions. Damasio (1989) specifically argued that recall and recognition involve reactivation of the same areas that were involved in initial registration of conjunctions. This is done by means of ‘convergence zones’ that enable retroactivation of multiple regions in the brain.

The crux of the reentrant theory is that brain processes are inherently iterative because of the hierarchical nature of the system and the fact that as information is processed in the higher areas the receptive fields become larger and lose their feature specificity. Thus, one or more cycles are required to establish a stable representation. Reentrant processes not only help to confirm what is correct but also resolve competition and thus allow accurate bindings to take place (Bullier, 2001; Di Lollo, Enns, & Rensink, 2000; Hamker, 2003; Hochstein & Ahissar, 2002, Lamme & Roelfsema, 2000).

As far as the visual system is concerned, such signals probably emanate from the parietal cortex. Saalmann, Pigarev, and Vidyasagar (2007) studied how parietal output influences early sensory areas in macaques performing a visual matching task. They found that output from parietal areas increased activity in the early areas, and concluded that this represented top-down feedback from the parietal cortex to early sensory areas that helped to focus attention on relevant locations. Silvanto, Muggleton, Lavie, and Walsh (2009) used triple pulses of TMS over PPC to find that they led to excitation in the visual areas when applied unilaterally, demonstrating the top-down modulation of the visual areas by PPC.

Reentrant connections in the brain may also be combined with dynamic changes in synchronous activity to explain how the bound object is distinguished from the background, or indeed from other objects (Seth, McKinstry, Edelman, & Krichmar, 2004; Van der Togt, Kalitzin, Spekreijse, Lamme, & Super, 2006). Thus, reentrant processes are now accepted to be crucial for binding. Indeed, so compelling is the evidence that it has led to a rethink regarding the very concept of binding among many researchers. There is a clear and discernible shift from the assessment of binding as a product to conceptualising it as a process.

Treisman (1996) proposed three sequential mechanisms to solve the binding problem: selection of particular locations by a spatial attention window, inhibition of locations from feature maps containing unwanted features, and top-down activation of the location containing the currently attended object for further processing. She also speculated that reentry to area V1 or V2 mediated all these three different mechanisms, proposing that reentrant connections from parietal areas mediate spatial attention, from extrastriate areas mediate feature based selection, and from the inferior temporal cortex mediate object based selection. Treisman (2006) holds that the initial response of the brain is to activate feature detectors in the early striate and extrastriate areas that automatically connect to compatible temporal lobe object nodes, and perhaps inhibit the conflicting ones. Parietal cortex then controls a serial reentry scan of the V1 and V2 areas to retrieve the features present in each, and then these are combined to form integrated object representations or bindings.

Humphreys (2001) and his co-workers also propose a two stage account of binding (Braet & Humphreys, 2009; Cinel & Humphreys, 2006; Humphreys, Cinel, Wolfe, Olson, & Klempen, 2000; Humphreys, Hodsoll, & Riddoch, 2009). The initial evidence for this two stage process came from a patient GK with bilateral parietal lesions (Humphreys et al., 2000). The patient could bind form elements into shapes, but could not integrate shapes with colour. This prompted the idea that the initial stage of binding results in shapes, and thereafter, surface features are associated with the shapes. Cinel and Humphreys (2006) proposed that in the initial noisy stage, visual elements are weakly bound, and these bindings can dissipate unless they are consolidated into more stable and stronger representations by being reinforced by top-down attentional feedback modulated by the posterior parietal cortex. Humphreys et al. (2009) showed that form conjunctions were easier to detect than difficult feature targets by controls and parietal patients alike, whereas parietal patients were significantly impaired in detecting other cross-domain conjunctions. Braet and Humphreys (2009) respectively used feature detection errors and conjunction errors as inversely related measures of feature detection and binding, and found that a patient with bilateral parietal lesions generated illusory conjunctions with unusually long display durations. Also when TMS was applied to the PPC area in normal participants, it led to an increase in conjunction errors, but only 150-200 ms after stimulus onset. Thus, they held that binding occurs due to reentrant communication emanating from the PPC.

Roelfsema (2006) postulates two mechanisms in the visual system responsible for binding, base-grouping and incremental grouping. Base-groupings are coded by single neurons tuned to multiple features, and reflect the selectivity of feed-forward connections. But, all possible feature combinations cannot be coded by dedicated neurons. Therefore, a second, flexible form of grouping called incremental grouping needs to be posited. Incremental grouping augments the responses of the set of neurons coding separate features that are bound in perception. It takes more time than base-grouping because it relies on horizontal and feedback connections, besides the feed-forward ones. The modulation of neuronal response strength, i.e, the firing rate of neurons, during the incremental grouping stage parallels the behavioural fact that attention is directed to features that are indicated by the enhanced neuronal response, and those features are then bound together. Base grouping takes place initially in the system, followed by incremental grouping in the cortex. This basic theory has been enhanced to propose a computational model that predicts figure-ground separation as well as binding (Jehee, Lamme, & Roelfsema, 2007).

Zimmer, Mecklinger, and Lindenberger (2006) distinguish between transient binding and more durable binding, implying that different mechanisms bind features at different points in time, and/or a process of consolidation transforms transient bindings into durable bindings. Shifting the focus to a very late stage in the binding process, and thus, proposing an integrated model of binding in WM and long term memory, Murre, Wolters, and Raffone (2006) also distinguish between transient and permanent binding, suggesting that while the former reflects the capacity of WM to select task relevant information for processing, the latter is the capacity of the neural system to store coherent patterns in LTM. Their emphasis, nevertheless, is that there is a constant interaction between these two. “What is transiently bound in WM governs what is temporarily and eventually permanently bound in long term memory. In turn, what is permanently bound affects transient binding in WM. The interplay of these binding processes determines how the brain develops into a structured system that is cumulatively correlated with its environment, thus implementing a process that is able to lift itself to higher levels of cognitive functioning" (Murre et al., 2006, p. 244).

Emphasizing the top-down factors even more, Hommel and Colzato (2009) propose that memory for a binding is controlled by two kinds of priming processes. Offline priming happens before the stimulus is presented, due to foreknowledge about the relevant features, task instructions, manipulation of mental set, etc. Online priming is induced by stimuli that have entries in long-term memory, such as familiar objects. These are detected in a non-selective fast feed-forward sweep, followed by recurrent processes refining the input according to the operating principles of the attentional set for that task.

In line with these ideas, this thesis assumes that binding is a continuous process that begins with the sensory input which goes to myriad areas of the brain and ends when the bound object emerges in memory such that it is strong enough to be manipulated further for higher cognitive processes. Features are initially perceived together either through synchrony or by neurons coded to detect conjunctions. This integration is a largely automatic, non-conscious process, which thereafter is refined by iterative processes and ultimately allows differentiation and dissemination of information in conscious states.

The time period within which this process operates is extremely limited. Studying the time course of visual processing using ERPs with natural scenes in human participants, Thorpe, Fize, and Marlot (1996) showed that decisions regarding presence or absence of animals in a visual scene flashed for 20 ms could be observed as ERP negativity in the frontal areas around 150 ms after stimulus onset. VanRullen and Thorpe (2001) demonstrated that whereas categorization of targets (animals vs. vehicles) in visual scenes flashed for 20 ms could be observed in ERPs 75-80 ms after stimulus onset, the difference between targets and non-targets could be observed only after 150 ms, reaching significance at 160 ms. Roelfsema, Tolboom, and Khayat (2007) used multi-unit recordings from the brains of monkeys and observed that features are registered in 48 ms, bound as figures distinct from the background at 57 ms, and relevant figures are selected over irrelevant distracters after 137 ms.

Taken together, these studies suggest that whereas encoding of the stimulus dimensions may take less than 50 ms, and the differentiation of the object from the background happens shortly thereafter, their categorization takes place only around 150 ms, to be followed by further refinement of the objects by the mechanism of attention. This project is an exploration of the process of binding that results in coherent objects for further manipulation by higher cognitive processes, with a view to delineate the bottom-up and top-down processes which impact on this process of binding.

TOP-DOWN AND BOTTOM-UP INFLUENCES

The process of binding inevitably begins with the physical continua impinging on the sense organs. So the study of how these stimulus dimensions are represented separately and together is obviously a logical starting point for the exploration of the process. But it is equally true that the information regarding stimuli does not enter an empty box. The brain has its own ideas! The top-down control of behaviour by mental representations of goals, instructions, and ideas is perhaps as undeniable as the source of behaviour in bottom-up processing of stimulation. A logical assumption is that since the reentrant signals emanate from the cortex, they reflect top-down modulation of the process of binding. Further, these signals assume even more importance when the original stimulus is no longer there, and the participant has to rely only on memory to maintain and process the stimulus further.

The psychological prototype for models emphasizing the utility of memory in online processing and manipulation of material in the service of current goals is the idea of Working Memory (Baddeley & Hitch 1974; Baddeley & Logie, 1999) which emphasized that different kinds of information are processed by distinct mental systems that act together to deal effectively with tasks confronting a healthy human adult. Baddeley and Hitch (1974) distinguished two subsystems, the phonological loop and visuo-spatial sketchpad, and a control system called the central executive. To deal with the fact that the information processed in these subsystems is often combined, and indeed, is at some stage also linked to information in the long term permanent store, Baddeley (2000) proposed a fourth component, the 'episodic buffer'. The episodic buffer was initially theorized to be controlled by the executive, but was primarily a storage system linked to conscious awareness, that binds together information from different sources in episodes. Thus, the episodic buffer was proposed as the answer to the binding problem (Baddeley, 2003).

Logie (2003) conceptualized WM as a mental workspace that deals with integrated objects identifiable on the basis of prior knowledge. He maintains that sensory input reaches WM only after it has activated the knowledge base. Thus, what reaches the workspace is the result of an amalgamation of the sensory input and the knowledge base. Since another source of input into the workspace is retrieval generated by processes in WM such as imagery, he holds that WM does not act as a gateway for processing information into LTM (substantiated by Van der Meulen, Logie, & Della Sala, 2009). The workspace model implies that feature binding takes place concomitantly with or before the object representation evokes prior knowledge, which in turn, precedes the manipulation of the object in the mental workspace. Nevertheless, other kinds of binding, such as between objects and their semantic associates, or between percepts and images, or between images, or among sequentially presented objects, presumably takes place in the workspace that is WM. The basic units in WM are thus perceived objects. On the other hand, the model can also be interpreted to accommodate the idea that features themselves might evoke prior representations in LTM and then the processes of WM refine the representation so that it emerges as an object.

Though there are many interpretations of WM as a concept and consequently many different models exist in current literature (reviewed by Miyake & Shah, 1999; Osaka, Logie, & D'Esposito, 2007), consensus on two characteristics that are important for this thesis must be mentioned. First, there is a general assumption that physiological level explanations are tenable for the WM phenomena observed at the behavioural level. Second, attention has a crucial and largely inhibitory role to play in all models of WM. Both these characteristics imply that WM is the top executive, the ‘controller’, managing the stimuli. It is in this sense that one may conceptualise WM as the source of top-down influences.

Certainly, this is how the advocates of top-down processes invoke and use the concept in their theories. The biased competition theory by Desimone and Duncan (1995) proposed that WM content in terms of instructional set, task goals, etc. facilitates the selection of matching sensory input. The biased competition model rests on the assumption that attending to an object causes a bias signal to be sent by higher areas to the lower sensory areas, which increases their tonic activity without necessarily increasing the neural responses evoked by the external stimulus itself. Behaviourally, this assumes that incoming sensory stimulation is matched with a template which specifies the relevance or otherwise of the received stimulation. Though Duncan (2006) concedes that in principle, competitive bias can begin anywhere in the system and then spread to the higher and/ or lower levels, he also reiterates the role of task relevance and an associated pattern of fronto-parietal activity that he calls the multiple demand pattern because it is produced by many different kinds of cognitive demands. No wonder then that his theory is usually taken to be a prime exemplar of the emphasis on top-down processing.

Based on studies using single unit recordings in macaques (Chelazzi, Miller, Duncan, & Desimone, 1993), it was held that a state of competition always exists among the variety of sensory inputs at any moment. Stronger sensory inputs usually win out, but the representations in WM bias the competition such that inputs matching them are the ones that are strengthened and selected for further processing. The contention that competition is essential for attention to emerge is supported by neuroimaging evidence that the posterior parietal cortex, which is activated when visuospatial attention is focussed, promotes feature binding when there is a potential for confusion with the simultaneous presence of other objects. Kastner, De Weerd, Desimone, and Ungerleider (1998) used fMRI evidence to substantiate that when stimuli are simultaneously presented, their cortical representations interact in a competitive and suppressive way in the ventral (object recognition) pathway. However, this was not evident when stimuli were presented sequentially. In a second experiment, spatial attention focussed on the objects was found to counteract the suppressive effect, and more so in the simultaneous as compared to the sequential presentation condition. Using fMRI, Shafritz, Gore, and Marois (2002) established that the posterior parietal cortex was active when multiple objects were simultaneously presented, but not when they were sequentially presented in the same location (at fixation).

Currently, there is conflicting evidence regarding the level to which distracters are represented in the brain. Some researchers propose that all objects and features are automatically and implicitly represented in the brain up to a level that excludes semantic processing (reviewed by Thoma, Hummel, & Davidoff, 2004). Nevertheless some studies indicate that even unattended objects are habitually processed to the semantic level (Altman, Grodd, Kourtzi, Bulthoff, & Karnath, 2005; Pins, Meyer, Foucher, Humphreys, & Boucart, 2004). Attempting a resolution, Martinovic, Gruber, Ohla, and Muller (2009) used EEG evidence to find that induced gamma band activity was enhanced due to the presence of distracter objects under low load conditions, thus providing evidence for cortical representation of distracters. However, as perceptual load increased, attentional selection played a more important role, and gamma band activity was limited to the attended object with a general suppression of all activity linked to surrounding information. This again corroborates Duncan's views regarding suppression of distracters by attention in consonance with top-down directions.

Emphasizing the integrated nature of processing of objects, Duncan (1996, 1998, 2006) held that since the object features are encoded in an integrated fashion across different cortical regions, if attention is directed to one feature, all features of the object, whether relevant or irrelevant, become dominant in their respective regions of the brain. Support for this idea came from fMRI data by O'Craven, Downing, and Kanwisher (1999a, 1999b) who found that neural activity increased in response to the attended as well as non-attended task irrelevant attribute of the stimulus. Nevertheless, their studies also provided evidence for differential levels of activity, with the absolute amount of activity being stronger for relevant features than for irrelevant ones in the attended object. More definitive data were provided by Schoenfeld et al. (2003) who recorded event related potentials as well as event related magnetic fields together with fMRI to find that the irrelevant feature was activated rapidly enough to participate in the perceptual integration and binding of the attended object. Using event related potentials, Winkler, Czigler, Sussman, Horvath, and Balazs (2005) found evidence that pre-attentive binding of relevant as well as irrelevant features occurs “normally” in visual as well as auditory modalities, and that attention is required for correct binding only under special circumstances when high load displays are processed under high time pressure.

Thus, in considering the difference between relevant and irrelevant information, the distinction between features and objects is crucial in Duncan’s theory. Duncan (1980) asserted that only targets are selectively processed through the limited capacity system, non-target objects are identified and rejected by initial parallel and unconscious processes. Nevertheless, this selectivity is not assumed to operate on features. Duncan (1984) showed that perceptual identification of properties inherent in two different objects is much more difficult than when the features are combined in a single object. However, if two features are combined within a single object the visual system finds it as easy to encode a combination of two features such as orientation and texture, as to encode them separately. Duncan (1998) provided evidence that it is also hard to identify two separate targets presented within the same modality, though there is no problem in detecting targets that differ between modalities. Thus, the features of an object are integrated such that they are processed together in an all or none fashion. Directing attention to a selected object enhances the representation of all its features together (Duncan, Humphreys, & Ward, 1997; Egly, Driver, & Rafal, 1994). The objects compete with each other and the winner is processed further at the cost of widespread suppression of the distracters or the to-be-ignored objects. Competition is biased and ultimately resolved in favour of task relevant objects, and typically, this state is achieved over 100-200 ms and is sustained by attention.

Luck and his associates also contend that the basic units on which VWM operates are objects rather than features. Luck and Vogel (1997) held that VWM was object-based because remembering one feature, such as colour, allowed the recall of another without any additional cost. Vogel, Woodman and Luck (2001) confirmed that VWM can hold 3-4 chunks of information, be they features or bound objects. This evidence suggests that VWM stores integrated objects rather than features, and objects rather than features are thus the basic units of VWM. Woodman and Luck (2007) tested the prediction of the biased competition model that a match between the template held in WM and the sensory input always leads to a facilitation of performance. They used a dual task paradigm and asked participants to perform a visual search task while maintaining object representations in VWM at the same time, but found no such facilitation of performance. Nevertheless, the reaction time was faster for matching distracters. When the participants knew beforehand that the target would never match the item retained in memory, they could direct attention away from the items that matched the WM representation. Thus, they found an inhibitory effect and concluded that participants can use the content of WM strategically to inhibit as well as facilitate attentional processing. Moores and Maxwell (2008) also found that prior stimuli in WM captured attention even in the absence of bottom-up priming, and influenced the response of the participant, despite the influence being detrimental to the task. Indeed one important purpose of VWM is postulated to be the control of eye movements (denoting attention), specifically the initial direction and subsequent correction of gaze towards particular objects in visual search (Hollingworth & Luck, 2009; Hollingworth, Richard, & Luck, 2008).

In contrast to these theories emphasizing the top-down nature of processing of integrated objects, are accounts of behaviour that stress the role of different features of the stimuli to be processed. These accounts vary in their espousal of top-down mechanisms. For example, the feature integration theory (Treisman, 2006; Treisman & Gelade, 1980) and contingent capture theory (Folk & Remington, 2006; Folk, Remington, & Johnston, 1992, 1993) ascribe paramount importance to top-down factors implemented through attention. At the other extreme are the accounts of stimulus driven capture (Theeuwes, 1992, 2004), and dimension weighting (Muller & Krummenacher, 2006a, 2006b), which primarily emphasize the importance of bottom-up factors in capturing attention. Nevertheless, they are similar in stressing one or more features as being important in the process of binding.

The feature integration theory (Treisman, 1988, 1998; Treisman & Gelade, 1980) suggests that attention to particular locations is the most important factor in feature binding, implying that all features present at a particular location are inevitably bound together if attention is focussed on them. Treisman and Zhang (2006) reiterated the importance of locations in binding in VWM as well. This view makes binding a relatively automatic process triggered off by attention to particular locations. It postulates a master map of locations, and as attention is focussed on any area of this map, the object in that location is encoded. Also, while detection of features is contingent on independent maps for each feature, other types of searches, particularly conjunction search, is driven by the master map of locations that integrates information from other maps to produce the signals that make each stimulus salient (Treisman & Sato, 1990; Wheeler & Treisman, 2002).

Kahneman, Treisman, and Gibbs (1992) proposed the object file theory, according to which objects are primarily identified by their positional marker or spatial index. Thereafter, other properties of the object, colour, shape, etc., are associated with the spatial index. Spatiotemporal continuity is essential for maintaining object file representations, whereas non-spatial properties such as colour and shape are unimportant. Direct evidence in support of this idea comes from the object reviewing paradigm (Kahneman et al., 1992; Mitroff & Alvarez, 2007), the multiple object tracking paradigm (Pylyshyn, 2004), visual search in dynamic displays (Alvarez, Konkle, & Oliva, 2007; Horowitz & Wolfe, 1998); and developmental evidence showing that young infants rely on spatiotemporal rather than surface features or identity information to make sense of their visual world (Feigenson & Carey, 2005).

Applying the feature integration theory and the idea of object files specifically to the binding process, Treisman (2006) maintained that pre-attentively, features and locations are registered in different maps, and focussed attention binds them together. She mentioned three components of the binding process, and suggests that we shift attention in space to select one object after another, suppress features of other objects, and finally bind selected features together into 'object files'. Note that she contends that initially, features are processed in parallel and stored as separate traces, which are only inhibited, but not completely eradicated, in the binding process. Revisiting the feature integration theory, Chan and Hayward (2009) have provided fresh evidence for dissociation between feature detection and localization, involving respectively parallel and focal search.

To completely grasp the implications of Treisman's ideas, it is instructive to contrast them with Duncan's model. One difference is their view of binding. For Duncan, binding happens at a very early stage in the visual process and the basic units in his theory are bound representations or objects. For Treisman, binding is a process of continuous refinement, during which features become linked to a master map of locations. Features remain bound only as long as attention is focussed on them. Any irrelevant features continue to exist in an attenuated form. Another related but important point of distinction lies in their disparate view of the role of attention in binding. While Treisman views attention to be a selective process essential for binding, Duncan assumes that features are already bound into objects (probably through conjunctive coding by neural detectors) and then biased competition between objects occurs accompanied by a state of attention. Attention is thus an emergent property of the system, and the mechanism that aids top-down biased selection of some objects over others. It follows that Treisman holds attention to be an earlier process than Duncan. Finally, the all important influence in the process of attention for Treisman is location, so attention is basically spatial in nature, whereas for Duncan, it is an emergent property of the system that is weighted in many ways, but essentially by task relevance more than anything else. Despite these differences, both agree that attention is necessary for binding separate features into a coherent object.

Treisman's insistence that attention was primarily spatial also conflicted with experiments showing attention capture by abrupt onsets, the tendency of anything unusual in the field to attract involuntary attention, even if participants are set to ignore them (Remington, Johnston, & Yantis, 1992). Nevertheless, the contingent capture theory (Folk et al., 1992, 1993; Folk & Remington, 2006) holds that attentional capture, as for example, by abrupt onsets, is contingent on top-down attentional control settings. This was because the original experiments showed that abrupt onset cues captured attention when the task was to identify onset target, but colour cues captured attention when the task was to respond to colour targets. Folk, Leber and Egeth (2008) have established that non spatial attention is also subject to capture that is contingent on top-down settings. In their experiments, a change in the colour of the distracter such that it matched the target, decreased target detection. Folk, Remington, and Wu (2009), showed that even non spatial distracters which did not capture attention, nonetheless, influenced responses to a target.

The guided search model (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989) had a rather different concern regarding the feature integration theory. Wolfe et al. (1989) pointed out that except for locations, the feature integration theory did not differentiate between other features of the stimuli. Further, it presumed that parallel processing of features in the initial pre-attentive stage did not have any impact on the later attentive serial search. The guided search model proposed that the features, which were processed in the parallel stage, guided attention in the subsequent serial stage, primarily by dividing the stimuli into distracters and probable targets. Further, they provided evidence that search for conjunctions defined by three features was more efficient than conjunctions of two features, simply because more number of features guided search for triple conjunctions. Wolfe (1994) acknowledged the special role of location by modifying the model to suggest that the output of processing in the initial massively parallel stage guided spatial attention and thus the second serial stage processed input from a limited portion of the visual field. Note that this reverses the sequence of the relative influence of location and other features postulated by the feature integration theory, which holds that other features are attached to a master map of locations and hence spatial attention precedes and guides attention to features (Treisman & Sato, 1990).

The idea that each feature is coded within its own feature map was extended by Vidal, Gauchou, Tallon-Baudry, and O'Regan (2005) to include the notion of 'structural gist'. Their Experiments 1, 2, and 3 using a change detection task with a study-test interval of 1000 ms showed that it was more difficult to detect changes of only colour, only shape, or only orientation, in a target item, if the distracters also changed on the same dimension as compared to a condition where there was no change in distracters. Experiment 4 showed that change detection was impaired when an item that remained on screen during the study-test interval changed in the same dimension as the target, demonstrating that encoding relational information was possible even when it was not presented simultaneously. In Experiments 5 and 6, they compared conditions when distracters could change on the same dimension as the target, or on a different dimension. Changes in a different dimension, however, did not have an effect on performance, whereas changes in the same dimension did affect performance. It was more difficult to detect feature changes when the distracters also changed features on the same dimension, as compared to when the distracters changed on some other feature dimension. Thus they proposed that each item in each feature map is encoded in terms of individual as well as configural information. The effects of relational information are particularly strong within each feature map. Their experiments considered only changes in colours, shapes, and orientation, keeping location constant. However, Jiang, Olson and Chun (2000) had earlier reported that detection of changes in colour was impervious to change in locations of non-targets.

The dimension weighting account (Muller & Krummenacher, 2006a, 2006b), which may also be considered an extension of the guided search model, holds that attentional weights are allocated to basic visual dimensions, (such as colour, orientation etc.), on the basis of stimuli defined by features (red, tilted, etc).

Enhanced feature contrast within a dimension e.g., red vs. green rather than yellow vs. green, and amplified saliency signals about a dimension to the overall saliency map, can facilitate detection of targets defined by that dimension, or alternatively target detection may be delayed if the target dimension changes across trials, shifting the weight to a new target defining dimension. They propose that the dimension weight can never be set to zero and indeed, may reflect the speed of processing associated with various dimensions. Weighting effects are proposed to be pre-attentive, influencing dimension based saliency signals before the overall saliency computation, which is the basis of attentional selection of objects. Nevertheless, weight shift can be modulated through expectancies set up by cues, instructions, past experience etc. In this sense the role of top-down processes is acknowledged. Muller, Geyer, Zehetleitner, and Krummenacher (2009) used the singleton salient distracter paradigm and showed how distracter influence varied with relevant practice, such that participants could learn to suppress distracters depending on the incentive to use suppression, which in turn, was presumed to vary with the probability of occurrence of the distracter. Nevertheless the costs of dimensional cueing in these studies could be, in part at least, due to task switching in general. Pan, Xu, and Soto (2009) studied the effect of dimensional cueing when the relevant dimensions were known to the participants. In fact, participants were explicitly instructed to prepare the relevant dimension on congruent trials and discard the irrelevant dimension on incongruent trials. Participants received a dimensional cue to be held in memory, and were subsequently tested on it either before or after a test of attention. Response latency was more on incongruent trials and less on congruent trials as compared to neutral trials. The benefits of congruency were enhanced when the cued dimension had to be held in memory throughout the trial, i.e., when the memory test was given after the attention test. This study demonstrates that the contents of WM can have an effect and in fact have more positive than negative effects on performance.

Theeuwes and his colleagues have consistently adhered to a strict bottom-up account of behaviour (Theeuwes, 1992, 2004; Theeuwes, Reimann, & Mortier, 2006). Their paradigm essentially investigates the effect of a singleton distracter defined by a different dimension than the one defining the singleton target. Theeuwes (1992) used a distracter defined by colour (the only red among all green), and a target defined by shape (the only diamond among circles). The initial check confirmed that RTs were quicker to colour than to shape, showing it to be more salient. Then participants performed under two conditions, one in which the distracter was present, and the other in which it was not. Results showed significant distracter interference in that RTs to the target were significantly slower when the distracter was present. The embarrassing question for adherents of top-down influences was why participants were unable to ignore the distracter; despite the fact that they knew the dimensions defining the target and the distracters. Recently, Schreij, Owens, and Theeuwes (2008) reported that abruptly occurring distracters produce costs in performance even in the presence of a top-down set for colour. They argue that these results show that abrupt onset of new objects captures attention independent of a top-down set and thus, provides conclusive evidence against the idea that attentional capture is contingent on top-down attentional control settings.

It is, of course, possible to take an eclectic view of the tripartite competition among researchers who have proposed objects, locations, or features to be the units of visual processing. Humphreys (1998) proposing a dual coding account of representation of objects in space, contends that we have a rather poor representation of space per se. However, objects are spatially represented in two ways, within object representations, where elements or features are encoded as part of objects, possibly in the ventral stream with some dorsal involvement; and between object representations, where objects are coded in relation to each other, presumably involving the dorsal stream. Both these kinds of representations exist in parallel. Visual processing capacity is limited by the competition to encode elements within an object, the number of objects that can be encoded at the same time, and the relevance of within object or between object representations to the task. In this view, unlike the feature integration theory, there is no attempt to assign a special role to locations. Indeed, the bottom line is that the objects in space are important. Space in itself is not represented. The feature that is important here is form, for form elements are bound in the absence of focal attention and are later associated with surface features such as colour. In giving this account, Humphreys also diverges from Duncan, and proposes that competition may exist within the elements of an object as well, and further, this competition can be biased by task relevance. Thus, the differential effect of features can itself be influenced by top-down factors.

Linnell and Humphreys (2004) have shown how object based selection can overrule the central bias, the fact that attention is primarily directed at fixation and performance decreases as eccentricity of the targets increases. Linnell and Humphreys (2007) used the odd man out paradigm of visual search and found that when the participants knew in advance about the feature defining a target, detection was enhanced due to grouping on that target feature, and the participants then limited search to that group only. This grouping by features overruled the central attentional bias by allowing the grouping of peripheral targets with centrally presented distracters. They concluded that visual search can be space, object, or feature based, and in fact, performance is often determined by an interaction of all three. The real winner is top-down modulation that directs which of these three are relevant to the task.

In fact, current research has largely moved away from this debate among objects, locations and features, to focus on *how* top-down WM factors influence the encoding and retention of stimuli. Both the content and capacity of WM are relevant factors in top-down influences. Early on, Pratt and Hommel (2003) found that features of objects in WM biased the selection of symbols (arrows) in the visual field, which in turn produced unintentional shifts in attention. Hester and Garavan (2005) demonstrated that both WM load as well as content had an effect on executive control of attention measured by task switching as well as a go/no-go paradigm.

An influential idea delineating how WM influences attention is the load theory of selective attention and cognitive control (Lavie & De Fockert, 2005, 2006; Lavie, Hirst, De Fockert, & Viding, 2004). It suggests that WM provides goal-directed control of visual selective attention by decreasing interference by goal-irrelevant distracters. Lavie and De Fockert (2005) tested this idea with the singleton paradigm. They showed that attention capture by an irrelevant colour singleton during shape search critically depends on availability of WM to the search task. When WM was loaded by a concurrent yet unrelated verbal short-term memory task, capture increased. Increasing WM load also results in greater distracter interference in Stroop-like tasks (De Fockert, Rees, Frith, & Lavie, 2001; Lavie et al., 2004). In fact, increasing WM load leads to greater distracter interference whereas increasing perceptual load reduces distracter interference (Lavie et al., 2004). Park, Kim, and Chun (2007) demonstrated that the type of WM load is crucial to this effect using the flankers task with houses and faces as stimuli. Distracter interference increased when the memory load items overlapped with the targets, but decreased when they were similar to the distracters. These findings suggest two selective attention mechanisms: a perceptual selection mechanism serving to reduce distracter perception in situations of high perceptual load that exhaust perceptual capacity in processing relevant stimuli and a cognitive control mechanism that reduces interference from perceived distracters as long as cognitive control functions are available to maintain current priorities (low cognitive load).

Forster and Lavie (2008) reasoned that in real life situations, there is as much need to avoid external irrelevant distracters as there is to suppress relevant distracters. Laboratory studies usually focus on relevant distracters alone. Thus they compared the effects of perceptual load on task-irrelevant and task-relevant (response competing) distracters. They found that an entirely irrelevant distracter can interfere with task performance to the same extent as a response-competing distracter. High perceptual load in the task eliminated the effect of both types of distracters with similar effectiveness. Forster and Lavie (2007) showed that though individual differences in reported distractibility was correlated with distractibility in a response competition task performed in the laboratory, high levels of perceptual load in the task reduced distracter interference for all participants. Forster and Lavie (2009) demonstrated how a high perceptual load, demanding task relevant processing, concomitantly decreased the frequency of task unrelated thoughts, and thus reduced ‘mind wandering’. When one needs to focus on a task, it is easier to inhibit both external and internal sources of interference.

Olivers, Meijer, and Theeuwes (2006) found that singleton distracters interfered more with visual search when an additional memory task had to be performed at the same time. The interference effect was even stronger when the distracters were virtually the same or related to the object held in memory. Houtkamp and Roelfsema (2006) studied whether items in WM influence the deployment of attention. Using line drawings of simple objects, they asked participants to remember two objects. After a blank interval of 1000 ms, while the participant was instructed to search for one of the two items as a target, the other memory item was sometimes presented as one of the distracters in an array of items. They found that the distracter had an effect only if the target was absent. Whenever, the target was present, the memory item had no effect as a distracter. Eyes were unlikely to be fixated on the distracter, and if they did, fixation duration was very short. Thus attention was primarily oriented towards the target, and memory items had an effect only if the target was absent. The special processing of the target has been found with objects in real world scenes as well. Details of targets and distracters related to targets are better retained than the distracters that are unrelated to the targets, maybe because they were looked at more frequently as shown by eye movement recordings (Williams, Henderson, & Zacks, 2005). Brisson, Leblanc, and Jolicoeur (2009) investigated whether contingent capture required capacity-limited central resources by incorporating a contingent capture task as the second task in a dual-task paradigm using N2pc as a marker of spatial attention. The N2pc was significantly reduced in high concurrent central load conditions, indicating that even though it is involuntary, the deployment of visual-spatial attention occurring during contingent capture depends on capacity-limited central resources.

Soto and Humphreys (2008) found that when the WM item that was used as a cue for one of the distracters, did not match the subsequent search display, search performance was worse as compared to a neutral baseline. This effect of WM content on search was reduced when cognitive load was increased, and when articulatory suppression was used. Soto, Hodsoll, Rotshtein and Humphreys (2008) reviewed evidence emanating from their lab regarding the influence of WM on search for relevant information from the environment. They contend that WM automatically guides selection, even if it is detrimental to performance. Further, on the basis of fMRI evidence (Soto, Humphreys, & Rotshtein, 2007) they assert that this modulation is a top-down process quite distinct from bottom-up processes such as priming. When a stimulus held in WM appeared in the search array, there was enhanced activity in the superior frontal gyrus, mid-temporal, and occipital areas. In contrast, implicit repetition priming (which involves mere repetition of a stimulus) elicited a suppressive response. In addition, WM probably affects the early process of attention that controls the entry of information into awareness. Soto and Humphreys (2009) assessed whether guidance by WM is limited to single task relevant dimensions, or does it differentially affect bindings of those dimensions. Participants were asked to remember the shape of a coloured object in memory. Then they were to search for a target line, amongst distracter lines, each embedded within a different object. On some trials, one of the distracter objects in the search display matched the memory item on the shape, the colour, or both dimensions. Relative to a neutral baseline, where there was no match between the memory and the search displays, search performance was reduced when a distracter object matched both the colour and the shape of the memory cue, demonstrating that WM had a greater impact on bindings as compared to single dimensions. Relevance of stimulus input to task goals thus seems to be the overriding factor in the process of binding.

Setting aside their differences, and focussing on the commonality, all models of top-down and bottom-up processing do uphold the idea that there is an *interaction* between top-down knowledge and bottom-up information. Essentially top-down knowledge helps set up criteria for the evaluation of incoming information, and the information that matches the criteria is given more weight and is processed further. Experimenters tend to use task instructions to set up such criteria. Vickery, King, and Jiang (2005) used different types of cues 200-1000 ms before a search array was presented, and thus varied the criteria from trial to trial. They found that detailed visual information such as orientation and size is more helpful in setting up a target template in visual search than conceptual properties of schematic or semantic nature, though the latter do have some effectiveness, and are better than completely uninformative cues. Also, whereas about 200 ms was sufficient time to set up the target template when defined by an exact cue (with some improvement shown till 500 ms), reaction time was faster to the word cues if they were presented 1000 ms before the search array. This study supports the idea that knowledge of exact stimulus properties may be more helpful in the initial stages of processing because these bottom-up features are what the participant relies on in the initial stages. Conceptual knowledge can be helpful, given sufficient time, as it takes time to encode the conceptual information itself or time is required to analyse and utilise it. Thus studying the interaction between bottom-up and top-down factors at various time intervals is seemingly an interesting project.

An experimental task involving binding is uniquely suited to study the factor of relevance in the transactions between bottom-up and top-down factors. Since by definition binding brings together various stimulus dimensions, the differences between dimensions should automatically affect performance. But if the result of this process of integration is an ‘object’, the process cannot be completely automatic; for it is then directed at the goal of generating a coherent object as defined by the task set, pre-existing knowledge, and so on. Which dimensions participate in the process can be biased by making some dimensions more relevant to the task as compared to the others.

Experiments 1-7 in this research are an attempt to explore the ambiguity in existing research regarding the extent and time course with which top-down signals regarding task relevance modulate the differences in the performance of the participants for different features in the process of binding. Using a variant of the change detection paradigm (described in detail in the next chapter) task relevance of a feature was manipulated by either randomising the feature on every presentation, thus making it completely irrelevant for performance, or by keeping it unchanged from study to test. The instructions to the participants were to ignore the irrelevant feature in both conditions and try to remember the binding between relevant features. The specific focus is on the question whether all features are bound together immediately or in the incipient stages of the binding process. Or, is it possible to ignore a feature from the outset if it is irrelevant to the task? Further, it is of interest to see if different features are processed at the same time and in the same way or if there are differences in their processing that persist beyond perception.

Since the aim was to study the effect of an irrelevant feature in an experiment, reducing the binding problem to its essentials, one ends up with stimuli which are defined concomitantly by at least three properties. The three features chosen to define the stimuli were location, shape, and colour. The experimental design renders a dimension completely irrelevant by randomising it from study to test. The participants know in advance that the dimension is to be ignored, that it is random and hence non-informative. This condition is compared with the other condition in which the feature remains unchanged from study to test, and hence might be used to remember the correct binding, despite instructions to ignore it and detect only the binding between the other two features.

If top-down influences are all-powerful, then the participants should be able to ignore the irrelevant dimension easily, and there should be no difference in performance in the randomized and unchanged conditions. However, if bottom-up influences are dominant, then a difference in performance between the two conditions is expected, with better performance in the unchanged condition. A third possibility is that bottom-up processes hold sway initially, but gradually the top-down processes take over. In this case, it is of interest to see when this happens.

It is also of interest to study if the same pattern is obtained for different features. Processing of features at different rates would index the importance of bottom-up information. Yet if the same pattern is obtained across the diverse range of features studied, it would indicate that top-down factors operate in a similar way across features.

DIFFERENCES BETWEEN FEATURES

Previous research has shown that there are important differences in the initial processing of features. Location is processed differently in comparison to other features, and there are differences in the processing of other features as well. However, it is not clear what happens when these features are integrated as a binding. Is detection and discrimination easier across channels for bindings as well? Does memory operate on features in the same way, irrespective of whether they are bound or not? Perhaps not, for there are clear benefits and costs to separate features when they are integrated in bindings.

The benefits of binding to the features involved are well understood and documented. Despite the fact that binding requires more resources to achieve, binding is usually held to be an adaptive process, which increases efficiency by making information processing more economical. Conjunction benefits have been demonstrated in visual search when the multiple features are all task relevant (Fournier, Bowd & Herbert, 2000; Fournier, Eriksen, & Bowd, 1998). The ubiquity of binding in all cognitive processes further confirms its generally beneficial role in behaviour. As far as memory is concerned, binding not only increases the capacity of WM as it allows chunking of stimuli impinging on the sense organs, it later facilitates switching attention from one object to another (Bao, Li, & Zhang, 2007). Nevertheless, binding is not always beneficial to memory. Guerard, Tremblay, and Saint-Aubin (2009) presented phonologically similar and dissimilar letters sequentially at different locations, to three groups of participants. The first group was asked to remember the letters in the original sequence, the second group had to free recall the locations (letters simply acting as markers for the locations), whereas the third group had to remember both until recall (the binding condition). Following the well-known effect of phonological similarity on verbal material, phonological similarity was detrimental to the recall of letters. Surprisingly, it was also found to be detrimental to the recall of locations. These results held in the single feature as well as the binding condition. The authors concluded that when one feature is vulnerable to a source of interference, other features also become vulnerable to that interference, simply because the features are held together in the form of a binding. Such benefits and costs of binding to memory for separate features argue against the idea that features are immune to the effects of binding and the system treats them the same way irrespective of whether they occur conjoined or separate.

One basic difference among features is that they are processed on different time scales. Numerous studies have demonstrated that various dimensions of the stimuli are processed asynchronously by the visual system (Aymoz & Viviani, 2004; Bedell, Chung, Ogmen, & Patel, 2003; Lamberts, 2002; Moutoussis & Zeki, 1997; Nishida & Johnston, 2002, Viviani & Aymoz, 2001, Zeki, Watson, Lueck, Friston, Kennard, & Frackowiak, 1991). Between colour and shape, it is debatable which is perceived first, and the answer depends on the kind of shapes used, but both are definitely processed much faster than movement. Psychophysical investigations into memory for features also suggest that information in VSTM is encoded in many different parallel channels (Magnussen, 2000; Magnussen & Greenlee, 1997; Magnussen, Greenlee, & Thomas, 1996). Detection and discrimination is easier across channels than within a channel. Multiple decisions required by increasing set size are also more difficult within a channel, though it is difficult to explain the step change in memory when set size is four vs. when it is more than four.

Lamberts and Kent (2008) investigated the time course of perception and recognition of three features, colour, shape, and orientation, as combined in either one or two study stimuli. Their work confirmed that perceptual processing of features happens at different rates, colour being processed the fastest, followed by shape, followed by orientation. Using a recognition paradigm akin to change detection, they also showed that the time course of retrieval of features mirrored that of perception, and thus differed for each feature, but only when the memory load exceeded capacity at six features (defining two different objects) to be remembered. There were no differences when only three features (defining one object) were to be remembered. Kent and Lamberts (2006) had already shown a similar linear relationship between encoding and retrieval rates in a cued recall task.

In keeping with these studies, Bartels and Zeki (2006) have shown that the processing of different kinds of binding also happens on different time scales. Interestingly, however, there is a reversal in the sense that binding of colours takes more time than binding of moving stimuli. Bartels and Zeki (2006) conclude that binding is different from, and subsequent to, stimulus processing and that it is an attribute-dependent, conscious process.

Location: A special feature

Location can be conceptualised in various ways. At the neural level, location can be coded in terms of the retinal image, relative to intended action, relative to other objects, or in relation to the surrounding environment. Explicitly, location can also be conceptualised as a descriptive property of a stimulus, much the same as shape, size, orientation, or colour. Among all these features, location seems *primus inter pares*.

The importance of location in perception is well established by studies showing that it is processed via the dorsal stream (Carlesimo, Perri, Turriziani, Tomaiuolo & Caltagirone, 2001; Funahashi, Takeda & Watanabe, 2004; Ruchkin, Johnson, Grafman, Canoune & Ritter, 1997; Smith & Jonides, 1995, 1999; Trevarthen, 1968; Ungerleider & Mishkin, 1982). The dorsal and ventral pathways are asymmetrically related, spatial localization occurring with the help of sub-cortical structures much earlier than object recognition and categorization, which are cortical processes, and are dependent on information resulting from localization (Vecera & Palmer, 2006; Velichkovsky, 1982, 2007).

Researchers have also contended that the parietal cortex is especially important in memory for locations. Patients with parietal lesions have reduced change detection performance for location but not colour or shape, patients with non parietal lesions showed no such impairment (Pisella, Berberovic, & Mattingley, 2004; Robertson, Treisman, Friedman-Hill, & Grabowecky, 1997; Treisman, 1998).

This is substantiated by psychological studies showing that the effects of location in visual search are largely independent of top-down factors such as task relevance.

Tsal and Lavie (1993) found that when participants were to respond to the colour of a dot, its location being task irrelevant, they responded faster to a probe in the same rather than a different location. Lamy and Tsal (2000) used a precue procedure to compare the effects of cueing for location or for colour and form. They found that cued object location was attended whether or not location was task relevant, whereas the colour and form were attended only when these were task relevant. Further, Tsal and Makovski (2006) assessed the allocation of attention to distracter and target locations as a function of participants' top-down expectancies. Participants performed a flanker task, and distracter locations remained fixed. On some trials, instead of the flanker display, either two simultaneous dots or a horizontal line appeared. The dot in the expected distracter location was perceived to occur before the dot in the expected empty location, and the line appeared to extend from the expected distracter location to the expected empty location, suggesting that attention is allocated, not only to targets but also to expected distracter locations, prior to stimulus onset. The authors propose that attention is guided to expected locations of all stimuli, regardless of whether they are targets or distracters. The differences among features have also been shown by Theeuwes and Van der Burg (2007) who used A’ as a measure of perceptual sensitivity in a visual search task. Location cueing was effective, but knowing in advance, whether the target differed in shape or colour, did not affect perceptual sensitivity, though it was easier to detect colour singletons than shape singletons.

Location has been postulated to be especially important in binding. The feature integration theory (Treisman, 2006; Treisman & Gelade, 1980) holds that in contrast to other stimulus properties, location has the special role of being the basis of binding of features into objects. In the prototypical visual search experiment, the participant has to find a target in a visual display. If the target is differentiated from non-targets only on a single dimension/attribute, the time required to differentiate the target does not vary with the number of non-targets present in the visual display. For example, when a red X pops out of a field of green Xs or red Os, whatever the number or density of the latter, processing is said to be pre-attentive. But if the target varies on the basis of a conjunction of visual attributes, for example if a red X has to be differentiated from among red Os (sharing colour) and green Xs (sharing shape), the time required to find the target increases with the number of non targets. Presumably, the latter requires more time because search is serial and attention can be directed to only one point at a time. The more the items in the display, the more the locations that must be sampled before the target can be located. Using such evidence, Treisman and Gelade (1980) proposed that directing attention to a point in space precedes the identification of information, which leads to the conclusion that directing attention to a particular spatial location allows the features at that location to be bound together so that an item can be identified. Treisman and Schmidt (1982) contended that if items are located at unattended locations, their features become ‘free floating’, and can be combined in an illusory manner. For instance if a red X and a green O are at unattended locations, an individual may report having seen a red O, wrongly combining one item’s colour with another item’s shape, and thus forming an ‘illusory conjunction’. Treisman and Sato (1990) held that different features are processed in independent stores, and are attached to a master map of locations in the process of binding by the mechanism of focused attention to specific locations.

The idea that location is especially important in feature binding is supported by experimental evidence from a variety of sources. Keele, Cohen, Ivry, Liotti, and Yee (1988) found that there is no tendency for synchronicity of features to cause binding unless they came from the same location, and thus concluded that location rather than temporal synchronicity is the essential cue for binding. Fahle and Koch (1995) used the ambiguous figure of the Kanizsa triangle to test whether the dominant percept is determined by spatial alignment or simultaneity of presentation of all elements. Spatial displacement destroyed figural binding, but even major temporal asynchronies had no effect on figural binding. Wheeler and Treisman (2002) showed that participants were better at remembering locations than colours. In fact, they obtained ceiling effects for the memory for locations, which also did not show any decrease as the number of stimuli increased from 3 to 6, thus substantiating their assumption that location is a special feature of multidimensional stimulus representations. In one of the reported experiments, they also randomized location to control its effect when the binding of shape and colour was tested, but they did not directly compare the effect of relevance of location on binding. Recent experiments by Treisman and Zhang (2006), however, showed that binding is more dependent on location than single features, though more so at 100 ms than at longer study-test intervals. Mitroff and Alvarez (2007) reported that contiguity in space and time rather than surface features, guides the persistence of objects, even if the object disappears for as long as 3 seconds.

When compared with other features, such as shape and colour, it appears that the distinctiveness of locations persists in memory as well. In ground-breaking research, Logie and Marchetti (1991) differentiated between the visual and spatial aspects of visuo-spatial memory. One group of participants were presented with arrays of squares, all in different shades of the same colour, for a very short duration, thus making verbal coding almost impossible. The second group saw the array presented sequentially. A recognition test followed 10 seconds later with the recognition sequence being identical except for a single change in either the shade of the colour or the order of presentation. The retention interval was either unfilled, or filled by unseen arm movements, or by irrelevant pictures. Results showed that arm movements disrupted memory for spatial sequences, whereas irrelevant pictures disrupted memory for colour shades. This indicated a distinction between memory for colour, and memory for location. Consequently, Logie (1995, 2003) postulated a distinction between memory for appearance of objects and for locations.

The difference in the study by Logie and Marchetti (1991), however, could also have arisen due to differences in simultaneous and sequential presentation. Darling, Della Sala, and Logie (2009) tested memory for visual appearance (font size) versus memory for locations, with the stimuli being presented either sequentially or simultaneously. Spatial interference from tapping or visual interference from DVN was presented during the retention interval. Although type of interference differentially affected memory for appearance and locations, results were not different for sequential and simultaneous presentation.

In the interim, other studies have substantiated the distinction between object and location memory using the dual task paradigm. For example, Postma and De Haan (1996) used a spatial reconstruction task with 4, 7, or 10 items presented simultaneously, asking participants either to pinpoint the locations or to put items in their original locations. Memory for locations was not affected by the number of items, but assigning items to locations was affected by set size and consequent cognitive load. Using an n back task, Postle, D'Esposito, and Corkin, 2005) found that object memory was sensitive to verbal rather than motion distraction, whereas spatial memory was more disrupted by motion than verbal distraction. They argued that object encoding necessarily involved semantic information, but this was not the case with spatial memory. Thus, the distinction between object and spatial memory was substantiated.

Using a change detection task to assess VWM for colour or form, Woodman, Vogel, and Luck (2001) found that performance on this task was the same irrespective of whether the subject processed 4, 8, or 12 squares in a visual search task given during the retention interval of the VWM task. However, when Woodman and Luck (2004) tested spatial WM, and inserted the same visual search task during the retention interval, they found a significant effect of set size of the search task. As the search task became more demanding, accuracy of memory for locations as well as the time taken to do the search task decreased. Thus performance was worse under dual task conditions than when either task was performed alone. Taken together, the two studies suggest that visual search reduced performance when spatial, but not object memory, was tested.

Turning to physiological evidence, Courtney, Ungerleider, Keil, and Haxby (1996) using PET found differential patterns of activation in the prefrontal cortex associated with memory for location and memory for object identity. Xu and Chun (2006) found that whereas memory for identity of objects recruited the superior intraparietal sulcus and the lateral occipital complex, memory for locations involved the inferior intraparietal sulcus.

All these studies substantiate the idea that visuo-spatial WM has two components, a visual cache that stores visual appearance in terms of colour, shape, size, etc., and an inner scribe that retains spatial information about locations, and movements between locations (Logie, 1995, 2003; Logie & Van der Meulen, 2009).

In all these studies, however, location was relevant for task performance. Though location holds sway irrespective of its relevance in the perception of stimuli, it may not be so for memory. One does not remember the location of every object encountered in the world. At some point, information about locations is lost from the system, unless it is crucial for achieving a goal. There are indications in literature that VWM is relatively immune to the importance of location of stimuli if it is not relevant to the task performance. In experiments by Phillips (1974) performance was better at short durations when test arrays were presented at the same location as the sample array, suggesting a retinotopic memory store. But, at inter-pattern intervals of 300 ms or greater, changes in the retinal location of test arrays had little effect on accuracy. Nevertheless, increasing complexity of the arrays significantly reduced performance. Consequently, he held that at longer intervals, performance was reliant on a limited capacity, short term store that was also relatively immune to masking.

Studying the characteristics of trans-saccadic integration, Irwin (1991) used 4×4 arrays of dots as the experimental stimuli, and in one experiment, found that displacement of the second pattern disrupted performance at 1 and at 70 ms, but had no effect at 600 and 5000 ms, the only inter-pattern intervals studied. Another experiment, studying the effects of spatial displacement over inter-pattern intervals of 70, 200, 350 and 600 ms, however, found null effects. Together, these experiments suggest that the disruption due to displacement disappears only at longer inter-pattern intervals. Irwin (1991) concluded that trans-saccadic memory is akin to the visual STM identified by Phillips (1974), in that it is a non-detailed, limited-capacity, relatively long lasting memory, which is not tied to absolute spatial position. Irwin (1992) reported that after an eye movement had occurred, the identity of letters presented in an array was retained much better than their position/ location, when tested using the partial report paradigm. Jiang et al. (2000), using a change detection task with the probe display presented 907 ms after the study display, reported that detection of changes in single items was reduced when the spatial configuration of array elements was changed. They concluded that though memory for the absolute location of single items is not important, the global configuration is important, and relational processing does take place for items in VWM.

Comparing memory at different time intervals, Van der Stigchel, Merten, Meeter, and Theeuwes (2007) asked participants to remember the location of a dot. When a task irrelevant stimulus was shown abruptly during the retention interval, not only did performance deteriorate in comparison with a control condition with no abrupt onset external event, but they found that the remembered location of the dot was shifted towards the location of the task irrelevant stimulus, suggesting an internal spatial map, when the onset was close to the memory representation. Wyble, Bowman, and Potter (2009) found enhancement in detection of a second target in changing arrays of 8 items when both targets were presented at the same location and the SOA between the two targets was 107 ms but not at 213 ms, as compared to a baseline condition with no leading target. When the targets were at different locations, performance was reduced.

However, none of these researchers explicitly studied memory for binding of other features in the absence of information regarding locations. Their focus was on testing memory for already bound objects. While Phillips (1974) used randomly lit cells of a square matrix as his test stimuli, Irwin (1991) used a 4×4 array of dots, Irwin (1992) used letters of the alphabet, Jiang et al. (2000) used green squares, geometric shapes, and novel shapes in different experiments, Van der Sigchel et al. (2007) used dots, Wyble et al. (2009) used letters. Perhaps the only research directly focussing on memory for binding of identifiable shapes and colour by studying swaps between these features is by Treisman and Zhang (2006). They showed that the impact of changing locations was much reduced at longer study-test intervals than at 100 ms. All these studies show that VWM is virtually immune to changes in locations, but only if it is not relevant for performance. It appears that task-relevance of a feature is a more important factor than the differential processing of features in memory.

Shapes versus colours

Shapes and colours were chosen as the two other features to define the stimuli in the experiments because of their differences as they represent respectively, boundary and surface features. Despite that shape and colour are both processed by the ventral stream, differences between the processing of these features have often been noted in perception. Which of the two is processed faster really varies from one research study to another, probably because of differences in the kind of stimuli used. Often, colour seems to be processed faster than shapes, but this may simply be because the colours used are more meaningful in terms of associations evoked, more distinguishable, or easily labelled.

Certainly, developmental and neuropsychological evidence suggests that shapes are ‘primary’ as compared to colours. There is a developmental dissociation between shape and colour processing. Needham (1999) has shown that infants can interpret objects as separate and distinct based on shape, but not colour at 4 months of age. They exhibit surprise when distinctly shaped objects move together, and when distinctly coloured objects move separately. One-year old children, use both shape and colour to individuate objects, but they still fail to notice colour changes after the object is hidden for a while, though they notice changes in shapes (Tremoulet, Leslie, & Hall, 2000). Thus, developmentally, the use of shape information occurs before colour information, in object individuation, as well as memory for objects.

The FACADE model of visual processing proposed that segregation of form elements is primary, and is followed by binding between forms and other features (Grossberg & Mingolla, 1985; Grossberg & Pessoa, 1998). The initial process of binding operates via a ‘boundary contour system’ to define shapes from the basic sensory input, and is sensitive to Gestalt grouping factors. Thereafter a ‘feature contour system’ fills in the surface properties. Still later, these interact with object recognition systems and spatial maps with the aid of attention (Grossberg, 1997).

Neuropsychological evidence with a binding task that was assessed on the basis of illusory conjunctions made by the patient GK, led Humphreys et al. (2000) to propose a two stage account of binding. In stage 1, form conjunction errors were more prevalent, and even more so when stimuli were presented simultaneously (allowing perceptual grouping) rather than sequentially, and to the same hemi field. Thereafter, in stage 2, form and surface conjunction errors were made. These were unaffected by grouping factors as well as whether items fell in the same or different hemi fields, suggesting that stage 1 occurred earlier in the visual processing system than stage 2. Additional evidence comes from Humphreys et al. (2009), who report that form conjunctions were easier to detect than cross-domain conjunctions between form, colour, and size, by controls and parietal patients alike.

In contrast, Song and Jiang (2006) held colour to be a simple feature, and form to be a complex one. They showed a sample array for 200 ms followed by a single probe after 900 ms. The stimuli were 1 to 7 coloured polygons and participants were asked to remember their colour, shape, or both. Behavioural performance showed that VWM capacity was 3 colours, 2 shapes, and 2 compound objects. Since colour was deemed a simple feature, whereas shape was conceptualised as a complex one, they concluded that capacity differences were affected by complexity of the stimuli. They also used fMRI and ascertained that the posterior parietal cortex was sensitive to difference between simple features as well as VWM load, the prefrontal regions to WM load, and the occipital-temporal cortex to differences among features.

Using a change detection task, Alvarez and Cavanagh (2008) have shown that storage capacity of VSTM was nearly twice as large for objects defined by boundary contour rather than surface texture. Since shapes are defined by contours and colour is a surface feature, this study implies distinctions between them too. In the detection of named targets among real life pictures shown in an RSVP stream, Meng and Potter (2008) found that even if 30% of the picture was occluded by dots, there was no effect on target detection, though recognition memory was reduced. Occlusion reduced detection if the picture was inverted, but merely taking colour away from the picture did not matter. Thus, form was more crucial than colour. The differential effects of colour-shape bindings on identification and memory for objects have also been documented by Lloyd-Jones and Nakabayashi (2009). Whereas identification was facilitated by the correct binding of the shape and colour of objects, this was not essential for memory.

The top-down vs. bottom-up debate in binding translates, in one way, as the relative importance ascribed to features. The bottom-up view holds that features are powerful enough to capture attention by themselves, and there are differences in the processing of different dimensions. Espousing a less extreme view either way, many researchers hold that location is a special feature in that it provides a framework to which other features may be attached. In contrast, the top-down view is that attention is essentially object focussed and only task relevant features are processed further. Empirically, the comparison between bottom-up and top-down processes in information processing has usually focussed on stimuli defined by single features. Proulx (2007) found evidence that bottom-up processes do play a role in visual search for conjunctions. Nevertheless, he also showed that bottom-up or top-down processing, or a combination of the two is a search strategy adopted by the participant according to the task demands, and in this sense, top-down processing is dominant.

Indeed, it appears that task goals and relevance to them are more important in VWM. Using eye movement technology, Richard et al. (2008) found that though it is possible to generate a saccade to the position of an object without encoding the surface features of that object, the reverse is never true. Whenever an oculomotor response is required, encoding of location is mandatory, whereas surface feature information is not a requirement. In this sense then, location is more important than surface features. Nevertheless, they also found that information regarding location as well as surface features, both helped to establish object correspondence, the information being weighted according to task relevance. If the participants were cued to look at a particular location, then spatial position dominated, but if they were cued to look at a particular colour, then colour played a dominant role in object correspondence. In this sense, the information regarding relevance of features overrides the differences in the features themselves.

Thus it is debatable whether the differences in features that are prevalent in visual attention and perception would apply in the operation of VWM in the few seconds after stimulus offset. In the present research, on the basis of the differences in the processing of the three features, it is expected that there would be differences in the time required to bind the two relevant features and ignore the third irrelevant one, across experiments 2, 3, and 4, as well as 5, 6, and 7. These differences among the three experiments in each set would also indicate the relative importance of the three features in the process of binding. However, if VWM treats all features the same way, then one might expect these differences to be present only in the initial stages denoted by the shorter study-test intervals, but not at the longer study-test intervals. Hence, a convergence of performance and an interaction effect over time is expected in each experiment, pertaining to locations, shapes, and colours, as well as across experiments.

THE SPOTLIGHT OF ATTENTION

Attention is the mechanism which implements the dictates of the top executive. It is essentially a selective mechanism that allows processing of only a few stimuli from among the multitude which the world comprises.

Since the embryonic stages of psychology, it is recognized that attention may be involuntarily captured by stimulus events, or it may be voluntarily allocated as derived from immediate task goals (James, 1890; Wundt, 1897). Accordingly, Posner (1980) classified attention as exogenous or endogenous. The former depends on cues in the external world that automatically draw attention, and is thus reflexive. Spatial cues, abrupt visual onsets, or salient visual features ‘capture’ attention (Foulsham & Underwood, 2009; Itti & Koch, 2000; Remington et al., 1992; Theeuwes, 1991, 1992). This ‘bottom-up’ stimulus driven attention is deployed automatically and rapidly, in about 100 ms, but is transient. In contrast, endogenous attention is deployed voluntarily, is effortful and slower to develop (takes about 200- 300 ms), but is sustained over a period of time (Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989). It is also ‘top-down’ goal driven attention (Yantis, 1998). Prinzmetal, Zvinyatskovskiy, Gutierrez, and Dilem (2009) have suggested that voluntary endogenous attention functions by perceptual enhancement of the stimulus focussed on, but involuntary attention affects the tendency to respond, irrelevant cues capturing attention away from the motor response.

Neurophysiological evidence suggests that whereas bottom-up exogenous attention involves both subcortical as well as cortical neurons, endogenous attention is entirely cortical in nature (Corbetta & Shulman, 2002; Kastner & McMains, 2007; Kastner & Ungerleider, 2000; Serences, Shomstein, Leber, Golay, Egeth, & Yantis, 2005). Using a rapid event related fMRI design with a visual search task, Talsma, Coe, Munoz, and Theeuwes (in press) showed that, in addition to a common network of parietal areas, the medial frontal cortex is uniquely involved in top-down orienting, whereas bottom-up control is mainly served by a network of occipital and parietal areas. Also, participants who were better able to suppress orienting to the colour singleton showed middle frontal gyrus activation, and the degree of top-down control correlated with insular activity. Thus, separate brain areas were involved in top-down and bottom-up driven attentional control, and frontal areas played a role in the suppression of attentional capture by an irrelevant feature, in this case colour. Generally, everyone agrees that there are complex interactions between bottom-up input and top-down mental set.

The role of attention in binding was first emphasized by Treisman and Gelade (1980) and has recently been substantiated by Hyun, Woodman, and Luck (2009) who used the N2pc component of ERPs as a measure of attention. They observed a larger N2pc component in the binding condition in comparison to a feature detection condition. In the interim, there have been a host of studies that have either supported or criticised the idea that attention is essential for binding. Recent experimental supportive evidence comes from Fougnie and Marois (2009), who found that memory for colour-shape binding, was more disrupted than the memory for single features when an attention demanding multiple object tracking task was given during the retention interval. On the other hand, some researchers have found that the same amount of attention is required for detection of features as for binding them together (e.g., Allen Baddeley, & Hitch, 2006; Johnson, Hollingworth, & Luck 2008; Joseph, Chun, & Nakayama, 1997; Kim & Cave, 1995; Theeuwes, Van der Burg, & Belopolsky, 2008) while others contend that bindings can be detected and maintained without attention (e.g., Eckstein, 1998; Gajewski & Brockmole, 2006; Mordkoff & Halterman, 2008; Palmer, Verghese, & Pavel, 2000). This equivocal evidence might result from different experimental paradigms, but it is more probable that it is due to the complexity inherent in the concept of attention itself.

Nevertheless, one point of agreement about attention is that it operates like a bottleneck because it has a limited capacity. The focus of attention determines what is selected for further processing. There is a debate though, as to exactly what it selects – objects, features or locations.

Feature based attention facilitates the guidance of attention to a target object only when location information is unavailable (Moore & Egeth, 1998, Shih & Sperling, 1996). Neurophysiological evidence suggests that spatial and feature based attention may not function additively (McMains, Fehd, Emmanouil, & Kastner, 2007). Zhang and Luck (2009a) have recently demonstrated that feature (colour) based attention can affect feed forward processing within 100 ms of stimulus onset, even for stimuli presented at an unattended location. The only condition for this effect seems to be that the stimuli must be presented simultaneously, i.e., under conditions of competition. Sequential presentation destroyed the effect. Spatial attention still remains special because it alone affects early processing even in the absence of competition.

While spatial attention may be contrasted with feature based attention on one hand, both are also distinct from object based attention. There is ample evidence for object based attention. It is easier to identify two features within a single object as compared with two features in two different objects, even if the two different objects were superimposed on each other in the same location (Awh, Dhaliwal, Christensen, & Matsukura, 2001; Duncan, 1984; Lee & Chun, 2001; Vecera, 1997; Vecera & Farah, 1994), and even when one object is partially occluded by another object (Behrmann, Zemel, & Mozer, 1998), and even when spatial cues were used to direct attention to a part of the display (Law & Abrams, 2002). The fact that visual search can be feature based has also been shown using a priming paradigm, where search is facilitated if the target shares features with the preceding target (Kristjansson, 2006). If the features lend themselves easily to object formation, then priming effects can be object based, but if they do not, then priming effects remain feature based (Kristjansson, Ingvarsdottir, & Teitsdottir, 2008).

It takes longer to move the focus of attention a particular distance between two different objects than it does to traverse the same distance if it is within an object (Egly, Driver & Rafal, 1994). When a cued object moves to a new location, attention moves with the object, rather than being tied to the same location (Kahneman et al., 1992). It is also possible to identify targets appearing within a cued object faster than an uncued object (Moore, Yantis, & Vaughan, 1998). Object based effects have been found for single region (Watson & Kramer, 1999) as well as multiple region objects as long as the multiple regions can be perceptually grouped together (Matsukura & Vecera, 2006). Proximity and connectedness of parts of the object promote the memory of objects as compared to features (Xu, 2006).

In all these cases, however, attention is directed to the relevant object with a cue *prior* to the response being given by the participants. Thus, these results can be attributed to the sensory enhancement of all features belonging to objects that have been *already selected* by attention. When Richard, Lee, and Vecera (2008) directly compared the prioritization (of location) and enhancement accounts of object based attention, the results supported the enhancement account. Using eye tracking, Becker and Rasmussen (2008) have shown with real world scenes that attention is first directed to locations and then to objects, and both are guided by familiarity coded in

LTM for scenes. Even more pertinent for the present research were results by Shomstein and Behrmann (2008) who have shown that object based effects show up better at longer exposure durations (1000 ms) than at shorter exposure durations (200 ms). Crucially, they also found that whereas 200 ms preview time is sufficient for object configuration to guide target detection, it is not powerful enough to show its effect in a more difficult target discrimination search task. It seems that attention to locations precedes attention to objects. All these studies support a rather speculative physiological account which suggests that early in the visual processing system, when magnocellular neurons are engaged by spatial attention, there is a concomitant inhibition of the parvocellular neurons which are sensitive to features such as colour and shape (Yeshurun & Levy, 2003; Yeshurun, 2004). In general, location seems to be a more powerful guide for attention.

Moving beyond the types of attention, consider how it functions. The oft used metaphor for attention is that of a spotlight. Does the spotlight simply tell us where or what to look at, or does it also blur our impression of the surround? The limited capacity hypothesis emphasizes the orientation function of attention (Eriksen & St. James, 1986; Henderson, 1996; Posner, 1980), whereas the noise reduction hypothesis suggests that attention excludes irrelevant noise that might otherwise interfere with stimuli in the focus of attention (Pashler, 1994; Shiffrin & Gardner, 1972; Shiu & Pashler, 1994). Behavioural evidence with spatial cueing seems to favour the limited capacity hypothesis, for spatial pre-cues shorten response latency and facilitate target discrimination even in an otherwise empty field (Henderson, 1996). Nevertheless, recent studies have shown that visual attention also suppresses the processing of irrelevant objects. Folk and Remington (1998) suggested that in the presence of irrelevant noise, voluntary attention imposes a filter on the incoming stimulation so that the target can be easily detected. It is the imposition of this filter that slows the detection or discrimination of the target. Wuhr and Frings (2008) found evidence for enhancement of relevant objects as well as inhibition of irrelevant objects as compared to a baseline, using the magnitude of the Stroop effect to assess the relative processing of objects.

Evidence from neurophysiological studies also suggests that a concomitant inhibition shows up whenever focussing of attention is studied. Two underlying neural mechanisms, gain and tuning, have been proposed to describe the effects of attention on populations of neurons (Hillyard, Vogel, & Luck, 1998; Lee, Williford, & Maunsell, 2007; Martinez-Trujillo & Treue, 2002, 2004; Maunsell & Treue, 2006; McAdams & Maunsell, 1999; Reynolds & Chelazzi, 2004). The gain model holds that the overall response to a stimulus is increased by a multiplicative factor across all feature detectors, increasing the effective signal strength. The tuning model holds that attention does not increase the response of any of the neurons. Rather it suppresses the response to irrelevant noise, leading to a narrower population profile. Of course, there remains a third possibility of a combination of these two. Ling, Liu, and Carrasco (2009) showed that whereas spatial attention operates by boosting the gain of the response, feature based attention operates by both boosting the gain and sharpening the tuning of the response. In keeping with these ideas, a psychophysical model, the Perceptual Template Model (Dosher & Lu, 2000, Lu & Dosher, 2005, 2008) postulates three mechanisms through which attention leads to performance improvements, stimulus enhancement, external noise exclusion, and multiplicative noise reduction. Lu and Dosher (2005) admit that they have never empirically observed multiplicative noise reduction. Nevertheless, stimulus enhancement and external noise exclusion are easy to distinguish empirically. Whereas the former improves performance only in zero or low external noise conditions, and is primarily associated with peripheral cuing, the latter modulates performance only in high external noise conditions, and is related to both peripheral and central cuing. Though the model systematizes the data in the field, it does not offer any new insights or make predictions beyond what the empirical data already show.

More recently, another function of attention, which may be called attentional protection, has been of interest. Matsukura, Luck, and Vecera (2007), used a double cue paradigm to compare the protection and prioritization functions of attention. The display was first cued to one side, and then to the other side during the maintenance interval. Their logic was that if attention merely prioritizes cued items in comparison to the others, then performance should be equally good for first cued or second cued item; whereas if it protects items from degradation during the maintenance interval, then participants should show superior performance for items cued first than second because the second cue is given to an already degraded set of items. They ensured that participants did not ignore the first cue by including some single cue trials. Their results showed that attention preserved items from decay and degradation during the study-test interval, thus essaying a protective function. This function of attention transcends the boundaries of perception and highlights how attention has a direct effect in the domain of memory.

Nevertheless, the role of attention in memory goes beyond protection, for memory is not only about storage, but also manipulation of memoranda. Attention has always been crucial in the models of WM (e.g., Baddeley & Hitch, 1974; Cowan, 1995; Engle, 1996), but it has been ascribed different functions in different models.

The multiple components model prescribes a paramount place for attention as a control process that directs all operations in WM. The initial concept of the central executive (Baddeley & Hitch, 1974) was that of a limited capacity pool of general processing resources that could be used for storage as well as attentional control (and possibly other functions too). But, Baddeley and Logie (1999) conceptualised it as an attentional control system alone, casting out storage from the central executive. Baddeley (2007) reiterates that the central executive functions in three different ways: focussing attention, switching attention, and dividing attention. However, ousting storage from the central executive necessitated the postulation of the episodic buffer as a storage system that brings together a variety of information from the other components of WM, perceptual input, as well as LTM (Baddeley, 2000). The buffer was not directly linked to the phonological and visuo-spatial stores, however, and presumably if phonological or visuo-spatial memoranda were to enter the buffer, they could do so only with the aid of the central executive. Attention was thus indispensible for storage and manipulation in the episodic buffer.

A central feature of the episodic buffer was "binding information from diverse sources into unified chunks" (Baddeley, 2007, p.148). Thus, attention was presumed to be essential for binding. Allen, Hitch, and Baddeley (2009) recently compared stimuli defined by binding of colour and shape presented visually, with cross modal stimuli for which either the colour was spoken as the shape was presented, or the shape was named as a shapeless blob of colour was presented. Performance was reduced by backward counting by threes, showing that the central resource of attention was important for performing the task, but cross modal binding was no more attention demanding than unified visual stimuli. Yet, revising their earlier idea (Allen et al., 2006) that bindings could be maintained automatically without using central resources, and the episodic buffer did not host visual feature binding, as a result of this and other fresh evidence (Karlsen, Allen, Baddeley, & Hitch, cited in Allen et al., 2009, p. 86), they speculate that binding does occur in the episodic buffer, which provides an arena for ambient attention, and is fed by a range of features and modalities. Focused attention merely serves to bias the contribution of these different features and modalities. This idea may be extended for the present thesis to suggest that focussed attention may influence the encoding and maintenance of goal-relevant features in binding, though it is not necessary for storage of bindings. Nevertheless, in a still more recent paper, available online in July 2009, based on work on binding or 'chunking' in sentences, Baddeley, Hitch, and Allen (2009) have again asserted that the episodic buffer is a passive store, which receives information from perception, LTM, as well as the phonological and visuo-spatial subsystems, with the process of binding as well as processing of bound representations occurring elsewhere, outside the buffer. They also hold that whilst the process of binding is automatic, processing of already bound representations uses the executive resource of attention. It appears that they believe binding to be the initial perceptual representation, which is the starting point of the *binding process* as conceptualised in this thesis, a process that results in a coherent object ready for further processing. From both the papers published in 2009, it also appears that the role of attention in the still developing concept of episodic buffer, especially with regard to the process of binding in VWM, remains to be resolved.

In contrast, the idea of focussed attention is the leitmotif of the embedded processes model (Cowan, 1995, 1999, 2005; Oberauer, 2002, 2007). Reminiscent of the spotlight metaphor, Cowan (1999) holds that the focus of attention is a subset of activated memory, which in turn is a subset of LTM. The focus of attention is controlled by voluntary as well as involuntary processes, and may be directed outwards at incoming stimulation, or inwards at the content of LTM, or away from irrelevant information in LTM as in inhibition. In the multiple component model of WM, attention is required for processing and some maintenance, but not memory storage itself, and thus tradeoffs within different domains of the model are held to be due to interference and not due to the limited capacity of attention. In contrast, Cowan's model conceptualises attention as a limited resource for which storage and processing are in incessant competition. Bunting, Cowan, and Colflesh (2008) demonstrated this by showing that when attention cannot be fully deployed at the time of encoding, it needs to be deployed at a later stage to bring the contents of passive memory in the focus of attention.

In keeping with his idea that attention is a domain general limited capacity resource, Cowan (2005) holds that attention is essential for binding. Indeed, binding happens as the object comes into the focus of attention, and a continued focus is necessary to maintain and retrieve bound objects from memory. While the focus of attention is limited by capacity, activated memory is limited by time. All stimuli activate some elements of memory, and when attention is focussed on some stimuli, their activation is enhanced. Thus one remains aware of at least the physical features of all stimuli, though one might habituate to them over time. Nevertheless, semantic features are not processed automatically, and require focussed attention.

Cowan (2001) also specifies that one can hold only about 4 items in the focus of attention, though he admits that items within this limited capacity set do not possess equal status. Oberauer (2002) formalized this idea to suggest that out of four it is possible to process and operate on only 1 or 2 items. In his model, the limited capacity region that Cowan calls the focus of attention is called the region of direct access. Within this region, Oberauer (2002, 2007) suggests a one chunk focus of attention.

A different function of attention, inhibition, is emphasized by researchers advocating an individual differences approach to WM (Conway & Engle, 1994; Engle, 1996; Engle, Conway, Tuholski, & Shisler, 1995; Engle, Kane, & Tuholski, 1999; Poole & Kane, 2009). Assigning a central role to attention in their executive attention theory, Engle, Kane and Tuholski (1999) postulate that WM equates attention plus STM (which they consider an activated portion of LTM). They also state that "WM capacity is not really about storage or memory per se, but about the capacity for controlled, sustained attention in the face of interference or distraction" (Engle, Kane, & Tuholski, 1999, p.104). Individual differences in WM capacity are shown in situations that require controlled attention of the type that inhibits irrelevant information, competing responses, and conflicting goals. It is used whenever the task demands errorless, perfect performance. The theory asserts that individual differences in WM capacity predict differences in a variety of tasks involving attention. For example, Unsworth and Engle (2005) demonstrated that WM capacity differences in learning sequences of asterisks in four locations emerged under intentional but not incidental learning conditions. Awareness was crucial for learning by high capacity participants.

In an attempt to specify the boundaries of the association between WM and perception, Kane, Poole, Tuholski, and Engle (2006) reported a series of experiments showing that WM capacity was unrelated with performance on visual search tasks which required a simple target present/absent decision irrespective of set size or complexity of the targets. In contrast, Poole and Kane (2009) tested participants on search tasks that involved either a short (300 ms) or long (1500 ms) focus on target locations either presented alone or mixed with distracter locations. They found that participants with higher WM capacity outperformed those with lower WM capacity, but only over long fixation delays and only in the presence of distracters. This suggests that the advantage of higher WM capacity is shown only in tasks when attention needs to be used to stop a response or to limit the focus, or in the words of

Poole and Kane (2009) for 'restraint or constraint'. Both these are anyway highly correlated (Friedman & Miyake, 2004) and may be considered different aspects of inhibition. Lower WM capacity participants cannot sustain a limited focus and are more susceptible to distracters.

To recapitulate the functions of attention in various models, while the perceptual models highlight what focussed attention can do – it selects stimuli, it prioritizes stimuli, it protects them from degradation; the memory models go beyond the focus to explore the boundaries of attention to specify what it does not do – it is limited in capacity, is relatively unimportant in maintenance, and it is not necessary for storage. They also differ from the perceptual models in their insistence that attention not only facilitates stimulus encoding, but is also crucial for the control process of inhibition. Finally, while perceptual models debate the crucial role of the bottom-up processes of 'attention capture', memory models are primarily concerned with attention as the central executive control mechanism.

Physiological evidence from ERPs also differentiates between the initial encoding involving attention and the later stages when the stimulus is maintained in VWM. The N2pc, a greater negativity at posterior electrodes on the side contralateral to an attended visual stimulus, usually lasting about 100 ms between 180 and 280 ms, is thought to reflect the moment-to-moment deployment of visual-spatial attention. It is established as the lateralized ERP component primarily underlying distracter suppression in tasks involving spatial attention (Luck, 1998; Luck, Girelli, McDermott, & Ford, 1997; Luck & Hillyard, 1994a, 1994b). Robitaille and Jolicoeur (2006) confirmed that N2pc is not related to the target alone. Rather it reflects processing related to the presence of a distracter. When a cue for the target was presented 100 ms earlier than the target, N2pc occurred earlier, and thus allowed earlier spatial selection and led to less interference from the distracter. Also, the offset of the N2pc was delayed when more interference from the distracter was expected.

A delayed contralateral negativity, named CDA, is also shown when participants are performing a VWM task with the amplitude of negativity proportional to the number of elements held in VWM as long as they do not exceed the capacity of four (Vogel & Machizawa, 2004). CDA is virtually identical with sustained posterior contralateral negativity (SPCN) that often begins about 300-400 ms after stimulus onset and that persists for the duration of the retention interval. A positive-going deflection at around 300 ms often separates the N2pc and the SPCN. The SPCN is also observed in tasks that are not defined as memory tasks, but that presumably engage visual short-term memory as an intermediate processing buffer (e.g., in order to make a choice response to a briefly-presented visual stimulus).

Using a masking paradigm, Robitaille and Jolicoeur (2006) found no differences in N2pc generated among a backward mask, forward mask, and no mask conditions. However, they did observe that the backward masking effect was significantly associated with sustained posterior contralateral negativity (SPCN; called CDA by Vogel & Machizawa, 2004) from 300 ms to 800 ms. This suggests that whereas the initial allocation of attention and concomitant distracter suppression is not affected by a pattern mask at the neural level, SPCN activity underlying VWM can be masked.

Jolicoeur, Brisson, and Robitaille (2008) dissociated spatial attention and maintenance of items in VWM indicated by these separate underlying ERP components, N2pc and SPCN. When memory load across trial blocks was manipulated by instructions either to encode only one stimulus or two stimuli, there was an increase in the amplitude of the SPCN as memory load increased, with no concomitant increase in the amplitude of the N2pc that immediately preceded it. The results provide a clear dissociation between the N2pc (spatial attention, not affected by memory load) and the SPCN (visual short-term memory, sharply sensitive to memory load). Thus, there is dissociation between attention and VWM maintenance in EEG measures, with different electro-cortical markers.

As may be clear from the foregoing account, the present work assumes that attention is a complex mechanism that has many roles to play in the binding process. Comparisons across experiments using blocked and mixed presentation of stimuli from among experiments 1-8, reported in Chapters 5, 6, and 7, specifically evaluate the effects of using an attentional set focussed exclusively on the task by clearly defined goals dictated by blocked presentation, against focussed attention on the task within a trial and shifts in set from trial to trial demanded by mixed presentation of trials. The experiments also yield interesting insights into the effects that various other types of attention have at different stages of the binding process, and are noted in the relevant discussions.

YINYANG: PROCESSES AFFECTING BINDING

Two processes which are often aided by the mechanism of attention but are basically different from it as they continue unabated in the information processing sequence are the opposite processes of consolidation and inhibition. Extremely difficult to separate empirically, they are conceptually quite distinct.

Consolidation

Over a century ago, Muller and Pilzecker (1900) proposed that initially fragile memories gradually consolidate over a period of time. The whole brain participates in this process of reorganizing and stabilising information. The dual trace hypothesis suggested that stabilization of reverberating cell assemblies underlying STM led to LTM (Gerard, 1949, Hebb, 1949). McGaugh (2000) reviewed evidence showing the selective action of drugs on STM and LTM to suggest that they are not sequentially linked and may be based on independent consolidation processes acting in parallel.

In this research, the primary concern is with consolidation in the initial few seconds after the stimulus is presented. It is quite well known that consolidation of one stimulus does not allow the consolidation of a subsequent stimulus that follows closely in time. The bottleneck may be at the encoding stage (Hommel & Doeller, 2005), or at the response selection stage (Pashler, 1994). Researchers have exploited this fact to their advantage by studying the time course and rate of consolidation when the participant is faced with doing two things at the same time. Consolidation problems are often cited as the primary reason for attentional blink and costs of dual task performance.

In the attentional blink paradigm, stimuli are presented at rates of up to 20 per second, and results show that if a second target is presented about 500 ms after the first target, it cannot be detected. Interestingly, if the second target appears in +1 position, it maybe processed together with the first one, and is reported reliably. This is known as Lag-1 sparing (Chun & Potter, 1995). Since studies have demonstrated that the second stimulus is perceived but not reported (Jolicoeur & Dell Acqua, 2000; Vogel, Luck, & Shapiro, 1998) explanations of AB have been proposed in terms of post perceptual processes, particularly the process of consolidation. Attentional blink has been thought to demonstrate that 200-500 ms was attentional ‘dwell time’ when attention was exclusively focused on a particular target, i.e., the initial target was being encoded or consolidated (Duncan, Ward, & Shapiro, 1994). The WM resource depletion explanation of attentional blink is that the first target is being processed by a limited capacity processor, and this impairs the ability of the system to process the second target (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Dux, Asplund, & Marois, 2008; Giesbrecht & DiLollo, 1998; Jolicoeur, 1998; Nieuwenstein, Potter, & Theeuwes, 2009; Vogel & Luck, 2002). Most recently, this explanation has been confirmed across three experiments by Dell'Acqua, Jolicoeur, Luria, and Pluchino (2009) who found no lag 1 sparing whenever the preceding target was correctly identified. However, Di Lollo, Kawahara, Sharab-Ghorashi, and Enns (2005) showed that participants can accurately report several target items if they occur in direct succession without any distracters. Thus, an increasingly popular explanation is in terms of inhibition of subsequent targets while distracters which follow the first target are being processed, either due to temporary loss of control (Di Lollo et al., 2005) or conversely, due to strengthening of control (Olivers, Van der Stigchel, &

Hulleman, 2007). In support of the inhibition view, Sy and Giesbrecht (2009) found that the magnitude of impairment in attentional blink was more when targets were similar on a task relevant dimension than on a task irrelevant dimension.

Research by Potter and colleagues throws light on the processes of consolidation in the incipient stages. Potter, Staub, and O'Connor (2002) used words presented in different streams in rapid serial visual presentation (RSVP) at 53 ms/item, with SOA varied from 0 to 213 ms. From 13-53 ms the second word was more likely to be reported, but at 213 ms, the advantage shifted to the first word, confirming two stages in processing, identifying a target, followed by consolidation of that target. The initial stage of target identification can be further subdivided into encoding and selection. Nieuwenstein and Potter (2006) compared partial report and whole report in an RSVP task arguing that both conditions required encoding, though only partial report required selection. The inferiority of partial report as compared to whole report was inferred as the cost of selection, which followed the initial encoding stage.

Jolicoeur and Dell'Acqua (1998) used the dual task paradigm, with the stimuli in the two tasks being presented in different modalities to reduce modality specific interference. The visual stimuli were 1 or 3 uppercase letters or keyboard symbols, whereas the auditory stimuli were pure tones of 400 or 1200 hz presented for 100 ms. Participants gave a speeded response to tones, pressing different keys in response to high pitched and low pitched tones, and thereafter, remembered and typed in the keyboard character(s) they had seen. Results showed that with increasing SOAs, the proportion of correct responses to tones increased, while the reaction time decreased. Also, a dual task slowing was observed, effects on the auditory RT being larger with a greater number of visual stimuli to be encoded. Jolicoeur and Dell'Acqua (1998) concluded that short-term consolidation is a highly capacity limited, slow, laborious process. Regarding the time course of consolidation their work suggests that encoding an item into WM begins shortly after the presentation of the visual display, and is almost always finished by 350 ms for single items. For a more complex task involving perceptual integration of arrays, Brockmole, Wang, and Irwin (2002) demonstrated that beyond 133 ms, performance improves and reaches an asymptote between 1000 and 1500 ms. Brockmole and Irwin (2005) assume that 1500 ms is the time required for the consolidation of a seven item stimulus into VSTM.

The masking paradigm has also been successfully used to study consolidation. Masks were initially used with the assumption that an immediate mask would eradicate the effects of iconic memory, but the delayed one would not. Thus Loftus, Johnson, and Shimamura (1985) used naturalistic pictures for varying durations followed either by an immediate noise mask or one after 300 ms. They found that the information available after the mask increased with an increase in the duration of stimulus exposure, though the decay of this information remained the same. They surmised an icon's worth to be equivalent to an additional 100 ms of stimulus exposure. Loftus, Duncan, and Gehrig (1992) replicated this work using stimulus arrays of four digits to be reported in their correct locations, for six durations ranging from 30 to 300ms, followed by a noise mask at six or seven stimulus-mask intervals ranging from 0 to 250 ms after stimulus offset. In all cases, they found that longer stimulus exposure durations yielded more information, suggesting that consolidation continued at least till 300 ms, though the rate of decay of the icon was the same irrespective of the stimulus–mask interval.

Bacon-Mace, Mace, Fabre-Thorpe, and Thorpe (2005) used dynamic patterns as backward masks at various delays to study the incipient stages of processing using gray scale natural images flashed for 6.25 ms, and found that performance steadily increased and reached an asymptote at about 40-60 ms after stimulus onset. They concluded that before 40-60 ms, the mask had essentially no effect because performance was largely determined by feed forward activity of neurons in the brain. The asymptotic performance observed in their study is remarkably similar to the 50 ms per item rate of consolidation reported by Vogel, Woodman, and Luck (2006) who studied the time course of consolidation in VWM for coloured squares using masks placed on the locations of the items in the visual array. They found that the first item is consolidated in about 60 ms, and thereafter the rate of consolidation is approximately 50 ms per item. Smith and Wolfgang (2007) compared the effects of simultaneous and trailing noise and pattern masks on detection of Gabor patches.

Though weak effects for integration masking were noted for simultaneous noise masks with low energy in one of the experiments, their major finding was that masking effects were larger with delayed masks presented 60-90 ms later, regardless of the kind of mask (noise or pattern), and the energy ratios for the mask and the target, again suggesting that detection of Gabor patches in the very initial stages could not be masked, and is probably dependent on feed-forward activity in the brain.

The rate of consolidation as 50 ms per item suggested by these studies is considerably faster than the estimates of about 500 ms for single items suggested by studies using the dual task paradigm such as those by Chun and Potter (1995), and Jolicoeur and Dell'Acqua (1998). Though none of these experiments studied the consolidation of bindings, in view of the fact that Vogel et al, (2001) believe that storage of features, conjunctions, and objects does not differ, it might be presumed that consolidation of bindings follows a course similar to consolidation of features. This easy inference, however, is complicated by the fact that complex stimuli require considerably more time for consolidation. Anaki, Boyd and Moscovitch (2007) have found that integration of three horizontal parts of faces presented sequentially requires about 700 ms. If bindings involve more information to be consolidated, and consolidation is resource dependent, then consolidation of bindings would certainly take more time, especially if there are irrelevant bits of information to be removed at the same time.

Woodman and Vogel (2008) used masks to study whether consolidation into VWM is a selective process. They used the change detection task showing the sample array for 23 ms followed by masks after 35, 105, 140, or 176 ms. The mask was shown for 500 ms and after a blank interval the whole display probe was given such that the test of memory was always 1500 ms after the initial display. Participants were to detect changes in colour, orientation, or conjunctions of three items in Experiment 1. In Experiment 2, the array consisted of seven items, and changes were to be detected in colour, shape, or conjunctions. Results showed that performance for colour was better than orientation, shape, and conjunction conditions; and this distinction emerged gradually as the stimulus-mask SOA increased. The results were substantiated by studying the CDA component of ERPs while the participants were asked to remember colour, orientation or conjunctions. The CDA component was larger for orientation and conjunction conditions as compared to the colour condition from 300 to 900 ms after the initial memory array was shown to the subject, confirming the selective maintenance of colour. It is to be noted that selective maintenance of relevant features emerges only with the passage of time, and is not shown during the initial stages.

It is clear from the foregoing review that though the term consolidation is used in many different ways, in this thesis it refers to the gradual encoding of material in VWM and is limited to the transfer of information from the sensory register to a relatively more stable representation in VWM. This is how many other researchers (Jolicoeur and Dell' Aqua, 2000; Vogel, Woodman and Luck, 2006) have used the term in the study of this process in the incipient stages of visual processing. Whether this transfer is aided by maintenance or elaborative rehearsal is beyond the purview of this thesis. The focus here is whether this transfer happens in an abrupt, all or none fashion.

Whether bound stimuli are processed in an all or none manner, or if consolidation is selective, implies the question if consolidation simply means transfer of objects from one store to another, or is it a continuous process of refinement of stimulus input. Basically, this asks whether consolidation is accompanied by inhibition.

Inhibition

Inhibition means the ability *not* to remember irrelevant information. Again, though the term is used in many different ways as will be clear from the following section, in the present work, it is used to refer to the process that is manifested by a lower initial performance in comparison with a higher performance when tested with an increased interval.

Inhibition is a critical component of an effective information processing system. In order to remember something, it is essential not only to consolidate the relevant information, but also to inhibit irrelevant information. Indeed the two processes are complementary and extremely difficult to disentangle in experiments. Nevertheless, the ingenuity of researchers knows no bounds, and a variety of experimental paradigms have been used to generate evidence for inhibition.

Object specific inhibitory effects are shown using the paradigm of negative priming (Tipper, 1985). In this case, participants are slower to respond to probes that serve as distracters on previous trials (usually the trial immediately before). The implication is that ignored items on previous trials were actively suppressed, and this inhibition is carried over to the new trial. Pictures can prime words and vice versa, indicating that this type of inhibition occurs at a semantic level (Tipper & Driver, 1988). Interestingly, such inhibitory effects are observed only when the target appears about 400 ms after the cue.

The phenomenon of inhibition of return illustrates location specific inhibition. It refers to the observation that participants show a transient bias against returning to locations that have been visited earlier. In experimental studies using the cueing paradigm, it has been found that cues facilitated target detection at specific locations, but only if the target appeared within 300ms. After 300 ms, target detection was slower (Posner & Cohen, 1984).

Feature specific inhibitory effects distinct from inhibition of objects and/or locations are relatively difficult to obtain. However, fruitful efforts in this direction have been made by Humphreys and colleagues. Watson and Humphreys (1997) devised the preview search paradigm in which a preview comprising a set of distracters (e.g., blue Hs) is shown for some time before showing the full display consisting of the target (blue A) as well as all the old (blue Hs) and new distracters (green As). Search for the target is much more efficient with the preview than without the preview. In fact search times often match the search times with only the new set of distracters present. It is as if the old distracters do not exist! As an explanation of the preview benefit, Watson and Humphreys (1997) proposed the mechanism of visual marking whereby the old items are inhibited. Since the preview benefit was disrupted by a secondary task done during the preview period (shadowing a series of digits at centre screen), they concluded that visual marking was a top-down process that was used only when necessary and when there were sufficient resources. Humphreys, Watson, and Jolicoeur (2002) found the disruptive effect with an auditory secondary task. Olivers and Humphreys (2002) presented an RSVP stream in which a target letter was to be identified, followed by a preview of green H distracters, followed by a set of blue items in which a target blue H was to be identified. By presenting the first target early or late in the RSVP stream, the attentional blink period was manipulated so that it coincided with the previewed distracters or not. When attentional blink and preview of distracters happened at the same time, the preview benefit was reduced, for attentional blink took away the resources, which would have been otherwise used for inhibition of previewed distracters. In contrast, when preview of distracters occurred outside the attentional blink, and one of them was made the target in the next subsequent display, search was slowed as the distracter inhibition carried over to the target in the next display (much like negative priming). All these studies substantiate that central attentional resources were being used for visual marking.

Several studies (reviewed by Olivers, Humphreys, & Braithwaite, 2006) show that the preview benefit is reduced if the new items share features such as colour, orientation, location etc. with the previewed distracters. Further, when participants are required to search for target letters among a set of randomly coloured distracter letters, search times can be reduced by giving information about the target colour, or presenting a preview of distracters in that colour. In fact, search times are best when both information and a preview are given. When there is a clash between prior information and preview, the preview effect holds irrespective of foreknowledge, suggesting that the effects are additive. This also indicates that the effect is feature based, though it may extend to objects as well. Allen, Humphreys, and Mathews (2008) extended the preview effect to photographs of houses and faces, which can be considered relatively complex stimuli. Goolsby, Shapiro, and Raymond (2009) also provided evidence of feature based rather than object based inhibition associated with distracter devaluation. Indeed, their data suggested that this inhibition is not only cognitive but also reduces the emotional value of stimuli (faces) which were shaded in a similar colour as previously seen distracters (Goolsby et al., 2009).

Visual marking, as originally envisaged by Watson and Humphreys (1997), was applied to the locations of the original items, but it is clear from the above studies regarding features that it is applicable to features other than location. It is thus, that visual marking is defined in a way that makes it agnostic to the feature vs. object, or location vs. objects debate. As Olivers et al. (2006, p.717) put it, “Visual marking is the top-down inhibition of irrelevant old information, in anticipation of the appearance of relevant new information”. Nevertheless, Braithwaite, Humphreys, Hulleman, and Watson, (2007) have somewhat reverted to the original emphasis on locations, holding that colour grouping enables the marking of locations, which are then inhibited.

Despite these myriad experimental paradigms contributing to the concept of inhibition, most of the literature is agnostic regarding further subdivisions of the concept of inhibition. Clearly however, not giving a response because of past experience is quite different from not giving a response due to present distracting influences, and both in turn seem distinct from suppressing a response to achieve a goal. In an attempt to delineate the boundaries of the concept, Friedman and Miyake (2004) used latent variable analysis to test whether the factor structure of inhibition followed their a priori tripartite division of inhibition. They started by postulating that inhibition is of three types: capacity to inhibit a prepotent response, distracter inhibition, proactive interference. Capacity to inhibit a prepotent response was assessed by a Stroop task, another task requiring the participant to respond to a stop signal, and an anti-saccade task. Distracter inhibition was measured by word naming, or matching shapes, under distracting conditions, and with a flankers task. Proactive interference was tested using the Brown-Petersen task, verbal learning for paired associates, and a cued recall task.

Results showed that a single latent variable accounted for inhibition of a prepotent response and distracter inhibition. This is understandable if one considers that a prepotent response also acts as a distracter at the time of deciding when or what response to give. A careful analysis of the six tasks used also allows the conclusion that all of them assessed interference during the decision phase before the response is given. A significantly different second variable underlying tasks involving proactive interference was identified. Both latent variables were found to be related with WM assessed by the reading span task, the correlation with the first one being -0.23, and the correlation with proactive interference being +0.33. Friedman and Miyake (2004) also found that the single latent variable accounting for inhibition of prepotent task and distracter inhibition was highly correlated (0.73 to 0.55) with tasks requiring the participants to switch attention, between semantic categories, or between number and letters, or between local and global features of a complex array. There was also a modest but significant correlation with the Cognitive Failures Questionnaire (Broadbent, Cooper, Fitzgerald, & Parkes, 1982), which assesses people on the frequency of everyday slips of action and attention. This pattern of correlations is important because the central executive in the multiple component model is ascribed three functions: focussing attention, switching attention, and dividing attention (Baddeley, 2007; Baddeley & Logie, 1999).

Within the WM framework, an inhibitory process was first proposed by Hasher and Zacks (1988). They suggested that the cognitive decline that comes with ageing is related to a reduced capacity for inhibition, i.e., keeping irrelevant information out. Lustig, May and Hasher (2001) hypothesized that this inability to keep irrelevant information out makes the elderly particularly susceptible to proactive interference. They tested this idea by abandoning the traditional way of assessing span by starting with one or two sentences, and instead tested the elderly starting with longer sequences. The elderly did indeed perform better when tested in this way. Younger participants did not show any benefit from this type of testing, but they did show a benefit from short breaks in testing which is traditionally associated with minimizing proactive interference. Based on his experiments comparing young (mean age 19 years) and old (mean age 69 years) participants on an arithmetic updating task and a recognition task, Oberauer (2005) concluded that older adults do not have problems in updating information and thus can inhibit current information as well as younger adults. But they find it difficult to reject intrusions from the LTM, which results in poorer performance on the recognition task. Hasher, Lustig, and Zacks (2007) reiterated that inhibition is the primary regulatory mechanism in WM and delineate three types of inhibition, access, deletion, and restraint (or suppression). Access represents the selection of relevant over irrelevant information for further attentional processing and is thus important at the time of encoding. Deletion refers to forgetting old irrelevant information, and works during storage. Restraint or suppression refers to the inhibition of response during the retrieval and response stage. Their research shows that all three vary within and across individuals, and across the life span.

Inhibition was also explored by Engle and his colleagues. In an experiment by Cantor and Engle (1993) participants were made to learn either a set of unrelated facts, or different facts relating to the same person (the fan condition). Then they were probed with a single fact to be assessed by them as right or wrong. The verification time was the measure of interest. Verification times increased with the size of the fan. They also showed that the fan effect was greater in participants with low WM span. Noting the similarity of this task with the probe technique used by Sternberg (1966) Conway and Engle (1994) found that low span participants showed a steeper decline in reaction times as set size increased. However, if the sets did not have any repeated items, the slopes were equivalent for low and high span participants, suggesting that low span participants were more susceptible to proactive interference.

Thus, Engle (1996) proposed the inhibition resource hypothesis proposing that all cognitive activity requires the capacity to inhibit input from competing stimuli and output in terms of alternative response tendencies, and asserted that WM is nothing but this capacity for inhibition. Kane and Engle (2000) used the classic proactive interference design with lists of words to demonstrate that low span participants were more vulnerable to proactive interference as compared to high span participants.

They also found a low but significant correlation between memory span and speed of response in the Stroop task, a classic measure of response inhibition. Low span participants found it particularly hard to give the correct response when the task was modified so that the ink and word were consistent 75% of the times. Conway, Cowan, and Bunting (2001) revisiting the cocktail party phenomena, asked participants to shadow a message played to one ear, while ignoring another message being played to the other ear. Unknown to the participants, the message to the other ear was interspersed with their own name. 65% of low span participants reported hearing their name, whereas only 20% of high span participants did so, showing that low span participants found it difficult to ignore distracters.

Since inhibition is linked to WM capacity, it follows that it is a resource demanding process, which is used only when necessary. Watson and Humphreys (1997) suggested that visual marking was used only in the presence of distracters and only if there were sufficient resources. Olivers et al. (2006) propose that the attention system may employ two independent sets: a positive set for target properties, and a negative set for distracter properties. The former allows consolidation and enhancement of target features, whereas the latter actively inhibits the distracter properties. Each is used as required.

Even more suggestive of top-down influences on feature binding, Hommel (2004) holds that initial binding of features is dependent on the task relevance of individual features, though he admits the possibility that highly salient but irrelevant features may also be activated to some extent. Extending the importance of relevant features beyond initial binding, Colzato, Raffone and Hommel (2006) showed that shape-colour binding effects disappeared with increasing practice when only one of the features involved was relevant to the task. Munneke, Van der Stigchel, and Theeuwes (2008) also found evidence for active inhibition when they cued the location of an upcoming distracter. This was found to reduce the effects of the distracter on the time required for target processing. They concluded that this was caused by active inhibition of the distracter location, which was cued 1500 ms earlier, the inhibitory mechanism being controlled by top-down settings.

Pylyshyn, Haladjian, King, and Reilly (2008) used a multiple object tracking task to yield evidence that non targets were inhibited if and only if they shared the criteria defining the target. The criterion in the multiple-objects tracking task being to track moving objects, they ascertained that non-targets were inhibited only if they were moving in the same plane. If they did not move, or if they moved in a different plane, they were not inhibited. In contrast even differently shaped targets were inhibited if they were moving.

Alvarez and Oliva (2008, 2009) have a somewhat different view regarding how distracters are dealt with. They propose that features outside the focus of attention are represented as 'ensemble features', a statistical summary, which compensates for the fact that representations lack precision and detail when attention is reduced or withdrawn. This also suggests a processing and consequent inhibition of features outside the focus.

The idea that inhibition is essentially a post-perceptual WM process is also substantiated by the fact that it takes time to develop. Attentional blink occurs at about 500 ms (Chun & Potter, 1995). Reaction times to targets at cued locations are stronger than those to uncued locations, but after 200 ms the reverse is true, and with inhibition of return, reaction times at uncued locations are stronger than those to cued locations (Maruff, Yucel, Danckert, Stuart, & Currie, 1999). The inhibitory effect of visual marking takes time to develop. In their original work, Watson and Humphreys (1997) found that the preview effect was much reduced when previews were given for durations less than 300 ms. Humphreys, Stalmann, and Olivers (2004) attempted to study the time course of visual marking. They compared probes presented at 200 ms and at 800 ms after previews to find that the preview benefit was much reduced at 200 ms. In fact, probes were more difficult to detect on old distracters than when they fell on the new distracters or neutral locations at 800 ms. In contrast, at 200 ms, detection of probes that fell on old distracters was facilitated as compared to when they appeared at neutral or new distracter locations. Braithwaite et al. (2007) have shown that in contrast to colour-grouping effects, which occur in the first 150 ms, colour-based inhibition takes time to develop and was best evident with a preview time of 1000 ms.

How behavioural data showing inhibition is implemented in the brain is crucial to our understanding the time course of inhibition. The basic fact to understand is that there is a relative lack of long range inhibitory projections in the neocortex, inhibitory activity of neurons being mostly local. Thus behavioural inhibition is actually represented as enhanced activity, i.e., excitation of neurons/ areas in the brain. The idea that behavioural inhibition is an expression of neural excitation is intriguing, but not really new. Indeed, it goes back to Descartes! fMRI studies clearly show enhanced activity in areas representing irrelevant information to be inhibited. One proposal is that inhibition is accompanied by the reentrant activity of long-range excitatory neurons which leads to more activity being recorded through fMRI in regions involving the to-be-ignored stimulus. This hypothesis may be termed ‘directed inhibition’. fMRI studies have shown increased activation in brain regions associated with behavioural results showing inhibition in anticipation of distracters (Serences, Yantis, Culberson, & Awh, 2004), with negative priming (Wright et al., 2006) and with the preview search procedure (Allen et al., 2008). Building on this, Herd, Banich, and O'Reilly (2006) have proposed that behavioural inhibition is ‘generated’ by excitation at the neural level. In contrast to directed inhibition, however, they propose that inhibition is an emergent property that reflects increased competition between various areas representing different features. This competition is modulated by task relevant representations in PFC. Active maintenance in itself involves competition, which is manifested in behavior as inhibition.

Many studies have shown the importance of the superior frontal sulcus and the intraparietal sulcus in visuo-spatial WM (e.g., Klingberg, 2006). Combining fMRI data and EEG recordings while a visuospatial task (reproducing sequential order of circles presented in a 4×4 grid) was performed, with a computational model, Edin, Klingberg, Stodberg, and Tegner (2007) have suggested a hierarchy in that stimuli (including distracters) enter the network primarily through the intraparietal sulcus, but directed strong activity from the superior frontal sulcus to the intraparietal sulcus offers protection against distracters, and this is the dominant network activity underlying visuo-spatial WM maintenance. Such a hierarchical network fits well with the idea that activity in the reentrant connections is responsible for inhibition of distracting stimulation which is such a vital aspect of maintenance in WM. McNab and Klingberg (2008) found that fMRI recorded activity in the prefrontal cortex and the basal ganglia preceded the filtering of irrelevant information, and predicted the extent to which only relevant information is stored in the parietal areas. This activity was also related to individual differences in WM capacity. In line with previous studies, McNab, Leroux, Strand, Thorell, Bergman, and Klingberg (2008) identified the right parietal region and the right inferior frontal gyrus to be activated together among participants who performed three tasks assessing inhibition and two WM tasks. Again, this supports the idea of a large overlap between WM and inhibition.

Considering the two processes of consolidation and inhibition together, the above physiological evidence suggests that the difference between the two is sequential. Initially, all features and objects are processed by the feed-forward mechanism presumably reflecting consolidation, but soon thereafter the inhibitory process kicks in and modulates the initial input. Eventually the object that emerges is a result of transactions between these bottom-up and top-down processes.

SPOTS OF TIME: MEMORY STORES

The percept, of course, persists beyond the time that it is actually present, as a rapidly decaying icon. So, what is the role of the icon in the arena where bottom-up and top-down processes are already competing? Does its influence simply decrease with time, or is it manipulated by the visual system. If the latter, does the visual system merely hold the information present in iconic memory as a template to match with the subsequent incoming stimulation, or does it continuously process and manipulate the information to facilitate further higher order processing?

Research on iconic memory really started with Sperling (1960). In one experiment, he presented three rows of four letters each to his participants for 50 ms. Participants recalled only about four letters. But when he presented a tone immediately after the array of letters, and asked the participants to report the top, middle, or bottom line, if respectively a high, medium, or low tone was presented, participants could still report about three out of the four letters shown. Since they did not know which row was to be reported, they must have had at least three letters from each row, i.e., nine items in their memory. When the interval between the offset of the array and the presentation of the cue was varied systematically, it was found that the partial report advantage steadily declined and disappeared at about 500 ms. Sperling (1963) varied the brightness of the blank field occurring before and after the stimulus array was presented, and found that if the stimulus array was preceded and succeeded by a dark field, the array could be retained for several seconds longer. This was evidence that people retained the array in a temporary store called ‘iconic memory’ (term coined by Neisser, 1967) heavily dependent on sensory stimulating conditions.

It was generally assumed that partial report performance relied on the persistence of the stimulus as an icon after the stimulus itself was no longer physically present. As the icon decayed, the superiority of the partial report performance over whole report was also lost. For example, using a change detection task in their experiments which showed that a location cue during the inter-stimulus interval resulted in better performance as compared to performance after a blank inter-stimulus interval, Becker, Pashler, and Anstis (2000) inferred that the first display is encoded as an icon, which is completely wiped out by the second display, unless the information is shielded from overwriting by focussed attention. However, this ‘traditional’ simplistic view of iconic memory as a passively decaying storage mechanism was challenged almost as soon as the seminal experiments on iconic memory were reported by Sperling (1960, 1962, 1963).

Averbach and Coriell (1961) used two rows of eight letters each followed by a bar as a location cue to indicate which letter was to be recalled by the subject. The accuracy of identification of the target letter decreased as the temporal interval between onset of the letter array and cue increased, but it never really dropped to zero. Rather performance stabilized or reached a plateau at about 30%. Thus Averbach and Coriell (1961) suggested that even before the cue was presented, the subject transferred information from iconic memory to a more durable store through a process of ‘non-selective readout’.

Erwin (1976) compared whether the icon was just a neural copy or echo of the stimulus, or a decaying non-functional one, or whether it reflects post sensory processes that organise and structure the information. His experiment compared a blank interval that allowed visual persistence, and a condition where persistence was substituted by the actual presence of the stimulus by cycling it with a noise mask for the duration that the visual persistence was estimated to last, and an immediate mask condition. He found that performance was best in the condition that allowed visual persistence, and thus concluded that processing of information continues after it is no longer present. The icon is a functional entity that interacts with and enables further processing of information into the STM. It is not just a copy of the stimulus that decays over time.

Averbach and Coriell (1961) also used a mask to limit the amount of time the icon was available for the process of non-selective readout, and estimated the duration of the icon to be about 250 to 300 ms. Averbach and Sperling (1961) estimated that the icon may last for as long as 2 seconds when presented in dark fields, but less than 0.5 seconds for light fields. However, this duration of iconic memory by the indirect method was found to be a gross overestimate when the more direct method of asking the subject to click to the offset of the visual image was used by Appelman (1980), to find that the icon lasted barely for 150 ms. Since a memory load of retaining distracter items affected the partial report estimate (Chow & Murdock, 1975; Sakitt & Appelman, 1978), but not the estimate from the direct click method (Appelman, 1980), it further indicated that studies of iconic memory using the partial report procedure were measuring performance based on iconic as well as a more durable non-visible memory component to which some information is transferred even before the probe occurs.

Coltheart (1980) explicitly recognised three kinds of ‘persistences of vision’; visible/ phenomenological, neural, and informational. After a careful review of the empirical properties of each, he proposed that visible persistence was the experiential correlate of neural persistence in the early visual system, and these were distinct from informational persistence or what he called ‘iconic memory’ (in the sense that information was retained but not ‘visible’). He used dissociation logic for this distinction, based on evidence that stimulus intensity and duration had inverse effects on visible and neural persistence, but they had no effect on informational persistence. He suggested that iconic memory (as he defined it) or informational persistence was not a peripheral sensory store; rather it was evidence for a central and relatively late stage of information processing. The distinction between visible and informational persistence was empirically confirmed by Loftus and Irwin (1998) who found inverse duration effects on objective as well as subjective measures of visible persistence, but not partial report performance. Di Lollo and Dixon (1988) using long stimulus durations and bright stimuli, did find evidence for an inverse duration effect in partial report performance, but only under high spatial demand conditions. This can also be considered as support for the idea that iconic memory relies on two components, one of which is retinotopic, whereas the other is spatiotopic (Breitmeyer, Kropfl, & Julesz, 1982, Feldman, 1985). McRae, Butler, and Popiel, (1987) tested this idea using four consonants to be reported in a left to right order. Local masks were used for a retinotopic representation, a spatiotopic representation, or both, and had similar masking effects resulting in lowered performance as compared to no mask as well as a meta-contrast mask control conditions. Given the temporal elements in the study, the researchers concluded that a spatiotopic buffer follows a retinotopic buffer.

Based on such evidence Smithson and Mollon (2006) asked whether a mask can really terminate an icon. They compared part report and whole report recall of an array of letters (<10ms) followed by a checkerboard mask (<20ms) after 0 or 100 ms. After the mask they presented a location cue (<20ms), asking the participants to recall the letter at the cued location. Six cue delays ranging from 100 to 600 ms were used. Performance was at chance when the mask was presented immediately after the array of letters for whole report as well as partial report. But, after the delayed mask (100 ms) there was a partial report advantage. Further, this advantage was greatest at the short cue delays, and gradually declined as the cue delays increased. Smithson and Mollon (2006) concluded that there is a second stage store which represents letters in terms of their higher level features, which the mask cannot penetrate, and hence the mask does not really terminate the icon.

Despite the debate regarding the nature of iconic memory, there is agreement that as per the classic model of information processing (Broadbent, 1958, Murdock, 1974) iconic store feeds a more durable memory store. The distinction between a sensory store and a relatively more permanent store was elegantly demonstrated in a series of studies by Phillips (1974), and Phillips and Christie (1977). Phillips (1974) differentiated between sensory storage and short term storage using checkerboard patterns varying in complexity by 4 to 25 cells, each of which could be lit up individually. A given pattern was presented and then shown again after a while with either a change in one of the cells or no change at all. The subjects were to respond same or different. Initially, performance was almost perfect, but it declined sharply thereafter. The initial levels of performance were immune to the complexity of the patterns, but with increasing delays, performance was higher for less complex (e.g., 4×4) patterns rather than more complex (e.g., 8×8) ones. There was also evidence that initial performance was dependent on a retinotopic trace, because when the second pattern was slightly shifted to the left or right rather than superimposed, the very high level of initial performance disappeared and performance reflected pattern complexity. Further, experiments using pattern masks showed that initial performance was affected more than delayed performance. The masks were checkerboard patterns comprising a 10×10 matrix with the same cell size as the test stimuli, and were presented so that there was a blank interval of 15 ms between pattern 1 and the mask and between the mask and pattern 2. Performance tests were at delays of 40, 80, 120, 300, and 600 ms. Masking was fully effective at the delay of 40 ms, even though the mask was barely detectable. Later, Phillips and Christie (1977) studied serial position effects for sequences of matrix patterns to conclude that visual memory had two distinct components, a one item recency component, which was unaffected by the rate of presentation, and a stable component which improved with slower rates of presentation, and had significantly longer recognition time than the recency component. The single item recency effect was observed whether or not the items were masked, but it was obliterated when the stimulus pattern was followed by mental arithmetic. They specifically stated that the stable component is not activation of LTM, and explained the distinction between recency and the 'stable component' by postulating a distinction between processing and storage within visual memory, with the processor having its own specialized storage system, analogous to a computer. Taken together, these studies provided evidence for the separation of a large capacity but transient sensory store, highly sensitive to masking; and a limited capacity, but more durable short term store (or multiple such stores), relatively immune to masking.

Once a distinct short term store for visual memory was identified, researchers veered towards ascertaining the capacity of this store. In an early experiment on immediate memory by Irwin and Andrews (1996), participants viewed a display containing letters in different colours. As they moved their eyes away, one of the letters was replaced by an asterisk. Thereafter, participants had to report either the colour of the letter, the letter itself, or both. Across set sizes from one to twelve, people could retain 3-4 items, and performed equally well whether both or single features were required. The stimuli used by Irwin and Andrews (1996) were verbal in nature. Luck and Vogel (1997) focussed exclusively on VWM using bars with different orientations as stimuli, combining them with colours and textures, to find that participants still encoded about four stimuli regardless of the number of features involved. In a subsequent extension of this study, Vogel et al. (2001) ruled out verbal coding by using shorter presentation times, difficult to name shapes, and a verbal load of two digits to be repeated throughout the trial. They found that subjects could still remember four objects, regardless of the number of features of which they were composed. Accuracy declined with increase in set size, but no forgetting was shown despite an increase in retention interval to 4900 ms. Cowan (2001) substantiated the limited capacity of VWM when he asserted that the focus of attention could cope with only about four chunks of information of any kind.

Wheeler and Treisman (2002) agreed that the capacity of VSTM is limited to 3-4 objects but held that features were independently coded in feature maps, and binding simply chunked the features together. Further, they asserted that binding required focussed attention, and costs of binding are evident only when whole display probes are used. Providing a signal detection theory account of change detection, Wilken and Ma (2004) have also agreed to the 3-4 item limit, but hold that it is explained by increasing noise in the internal representations due to set size. Otherwise, participants probably code stimuli independently and in parallel.

The fact that only 3-4 items can be consolidated into VWM (Luck & Vogel, 1997; Vogel et al., 2001) has been developed into the theory that only 3-4 ‘slots’ for discrete fixed resolution representations exist in VWM. Zhang and Luck (2008) assumed the probability of correct report to be a measure of capacity and standard error of mean (standard deviation divided by square root of N abbreviated in their paper as s.d) to be an independent measure of resolution. Using a recall test for coloured stimuli and set sizes of 1, 2, 3, and 6, they provided evidence that the 3 items encoded into VWM were of fixed resolution and were encoded in an all or none fashion. Similar results were obtained for shapes as well. Further, Zhang and Luck (2009b) studied the colour representations after 1, 4, and 10 seconds to conclude that the representations also decayed in an all or none fashion, dying a ‘sudden death’, in their words. However, in both studies the results for resolution are based on no differences in the data. Second, the set sizes of 4 and 5 were not studied, neither were the time intervals between 4 and 10 seconds. Thus, it is hard to draw conclusions regarding the nature of representations for these set sizes and durations, and therefore to adequately test the ‘all or none’ nature of representations.

Nevertheless, neuropsychological evidence for lateralized electrophysiological activity that represents encoding and maintenance in VWM also suggested that this activity reached an asymptote on an average around 4 objects, but the precise time when the asymptote was reached showed individual differences, as high capacity individuals reached the plateau much later than low capacity individuals (Vogel & Machizawa, 2004). Evidence from fMRI investigations of the posterior parietal cortex has also supported VWM capacity of only about 4 objects (Todd & Marois, 2004).

An advance on these results is research showing that, whereas the inferior intra-parietal sulcus represents objects at four different locations irrespective of complexity, the superior intraparietal sulcus and the lateral occipital complex track these objects held in the VSTM, and represent fewer than four objects as the complexity of the objects increases (Xu & Chun, 2006). Further, the intraparietal sulcus and the inferior gyrus are involved in selection and processing of both spatial as well as non spatial features, such as colour and orientation (Vossel, Weidner, Thiel, & Fink, 2009). Together, both these studies indicate that complexity of the stimuli is an important consideration in capacity estimates of processing in the parietal cortex.

Not surprisingly, researchers who emphasise that complexity or information load is the critical factor determining capacity of VWM have posed a significant challenge to the view that there are 3-4 fixed slots in VWM. These researchers hold that VWM is a resource that can be flexibly allocated to more or less representations depending on the complexity of the objects and the precision of the representation required. Alvarez and Cavanagh (2004) studied a broad range of stimuli using the change detection paradigm to conclude that performance declined with increasing information load. Franconeri, Alvarez, and Enns (2007) reported that when precise selection was demanded, only 2-3 locations could be selected, but when the selection region could be coarser, 6-7 locations could be easily selected. In contrast to studies showing that participants can track a maximum of four objects, Alvarez and Franconeri (2007) found that at slower speeds it was possible to track up to eight objects, whereas it was possible to track only a single object at fast speeds. Curby and Gauthier (2007) tested whether perceptual expertise enhances the capacity of VWM. Using a change detection task with upright and inverted faces as stimuli, they concluded that perceptual expertise in detecting upright faces did increase capacity. Makovski and Jiang (2008) compared VWM for simple and complex objects (defined in terms of goodness of figure) to find that visual search for embedded targets rather than distracters was faster, though this advantage diminished with increasing memory load. All these studies, however, studied within-category changes. Awh, Barton and Vogel (2007) compared within-category changes to cross-category changes using Chinese characters and shaded cubes as stimuli. They found that for within-category changes, capacity estimates decreased with increasing complexity (a result similar to Alvarez & Cavanagh, 2004). However, complexity of the stimuli had no effect on cross-category changes. Scolari, Vogel, and Awh (2008) compared small (within-category) changes with big (cross-category) changes to find that the latter were more easily detected but capacity estimates still did not exceed 4 items. They asserted that they had thus separately assessed VWM representations in terms of numbers and resolution. They concluded that perceptual expertise, having a greater effect on the detection of small changes and no effect on big changes, enhanced the resolution but not the number of representations in VWM. Franconeri, Lin, Pylyshyn, Fisher, and Enns (2008); and Shim, Alvarez, and Jiang (2008) established that it is object crowding which accompanies increased speed that is responsible for lower performance in tracking multiple objects at fast speeds. Obviously then, this debate about capacity and complexity seems to be heading for some sort of solution by considering number of items to be distinct from their resolution.

The view that out of the plethora of input, only 3-4 objects survive to enter VWM faces a more direct challenge by the evidence for larger capacity estimates in terms of number itself. Various studies have shown superior performance after a retro-cue than performance with no cues or with after cues (Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003; Lepsien, Griffin, Devlin, & Nobre, 2005; Lepsien & Nobre, 2007; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008). All of these studies have interpreted the result that the retro cue works by directing attention to the cued item, and thus enhancing its representation, making it resistant to interference from subsequent probe displays, or protecting it from forgetting. Though the cue is usually presented after a time delay well beyond the usual period associated with iconic memory, none of these studies was designed to rule out the conclusion that performance after a retro cue benefitted from iconic memory. However, Sligte, Scholte, & Lamme (2008) used the retro cue paradigm with masks presented before the cues to conclude that before the emergence of four objects in memory there is an intermediate stage which they named 'fragile VSTM' with a capacity of at least ten objects. More importantly, they contend that this store is 'information based' rather than retinotopic, and is thus distinct from iconic memory as well. This conclusion is based on their use of energy and pattern masks to disrupt retinotopic traces. Further, the retro-cue was presented much later than the duration that iconic memory is thought to last. Nevertheless they do acknowledge that performance of the participants might include a benefit from spatiotopic representation, in line with evidence from McRae et al. (1987). They also link this store to recurrent processing (and not feed forward sweep) in the brain which has been shown to be important for feature binding (Landman, Spekreijse, & Lamme, 2003) as well as figure ground separation (Landman, Spekreijse, & Lamme, 2004).

Using a mask to reveal effects

As is manifest from the foregoing discussion, masking has often been a useful paradigm to differentiate the effects of iconic memory and VSTM on performance as well as to study the process of consolidation. Thus it was also used in this research for these purposes. Masking may be generally described as the effect of one visual stimulus on another. At least three different kinds of masks may be distinguished, tied to the effects they achieve; energy, pattern, object substitution.

The use of a bright flash of light to impair reading an array of letters was first reported as early as the 19th nineteenth century by Baxt (1871). He also found that the number of reported letters increased in a linear fashion as the interval between the presentation of the items and the flash of light was increased. This was replicated and extended as a complete study of masking by Crawford (1940, 1947) following which backward masking was named as the 'Crawford effect'. He used a circular pattern of light presented in foveal view for 524 ms as the mask, and a 10 ms flash of light as the target, presented before, during, and after the mask. The target was most easily detected when presented simultaneously with the mask. He also noted that the mask influenced the target till about 100ms after the presentation of the target.

Pattern masking may be achieved by masking by noise or masking by structure (Breitmeyer & Ogmen, 2006, 2007). Kinsbourne and Warrington (1962) first reported masking by random dot patterns where there is no relation at all between the target and the mask. Many researchers assume it to be the archetype of masks. Perhaps this is why it is often used in various studies requiring masking but with little effect, except when the target stimulus is structurally similar. In contrast to noise masks, masking by structure involves varying degrees of resemblance between the target and masks in selected relevant dimensions, such as contours, colours, orientation, depth etc. Oyama, Watanabe, and Funakawa (1983) systematically investigated the effects of test-mask similarity on forward and backward masking over SOAs ranging from -100 to +100. They concluded that similarity yielded almost symmetrical forward and backward masking effects, but asymmetry in the masking effects maybe, and is often, caused by other factors.

Object substitution masking is a late and new entrant to the field. It was first described by Di Lollo, Enns, and Rensink (2000). They asked the participants to detect a target in an array which was labelled by four surrounding dots. Whenever the four dots remained visible after the target had disappeared, participants were unable to report the target identity. They argued that the masking mechanism here is object substitution. When the target information is relayed by feedforward mechanisms to higher processing levels in the brain, a perceptual hypothesis is formed. When masking occurs, it is because reentrant processes in the brain are unable to confirm this hypothesis, because the target is substituted by the four dots. Some researchers suggest that the input from the mask obliterates the initial object token (Jiang & Chun, 2001), whereas others suggest that object files are updated rather than created new (Enns, 2002; Lleras & Moore, 2003; Moore & Enns, 2004).

There is no doubt, however, that top-down processing plays a part in this type of masking. Masking is greatly affected by expectancies set up through task instructions, and is specifically reduced if there are expectancies regarding the target location (Enns, 2004). Woodman and Luck (2003) provided support for this idea from their ERP study showing that the target is identified and triggers a shift of attention, but by the time attention shifts to the target, only four dots are visible and so behavioural detection performance decreases. Weidner, Shah, and Fink (2006) used fMRI to identify the primary visual cortex, higher visual areas, and the intraparietal sulcus as the areas that are activated in effective four-dot masking, confirming that it is a central, cognitive kind of masking.

Comparing different kinds of masks, Jacewitz and Lehmann (1972) used energy and pattern masks to conclude that both affected memory performance for letters presented in a 3×3 matrix for 50 ms, though the pattern mask had a slightly greater effect. Letters and masks were presented to different eyes and yet interference was found. Following suggestions by Haber and Standing (1969), they concluded that at least a portion of iconic memory had a central rather than peripheral location. Turvey (1973) also explored the difference between different kinds of masking. An important feature of a brightness mask is the energy it contains. According to Bloch's law, the effect it has is a multiplicative function of its brightness and duration. Hence if a flash of light is presented for 200 ms rather than 100 ms, it will be twice as effective. Turvey substantiated Bloch's law for brightness masks. Also, a brightness mask was effective only if presented to the same eye as the target, suggesting that the mask interfered at the retinal level. In the case of pattern masking, however, presenting the mask to the same eye as the target, or to the other eye, made no difference. This suggests that the pattern mask affects processes beyond the point at which input from the two eyes is combined, i.e., at a central level. The crucial variable for the pattern mask was the interval between the target and the mask. The effect was additionally contingent on the target duration. Thus, the inference is that the onset-onset duration was the critical factor for the pattern mask.

Bongartz and Scheerer (1976) used a backward mask specifically to interrupt the process of 'naming' which was assumed to follow the initial process of 'selection', which transferred information from the sensory store to the short term store. They used a partial report procedure with the target being 4 rows of 12 letters or numbers shown for 100 ms, and either a colour or a location cue of 50 ms. In the first experiment, the cue preceded and followed the target by inter-stimulus intervals ranging from -500 to +500 ms. Performance measured in terms of percent correct was better for location cues than for colour cues, but converged and reached an asymptote at +250 ms. This led to the conclusion that the selection process which transferred items from the sensory to the short term store was complete by 250 ms. The second experiment was conducted to test the effect of a backward mask on the 'naming' process that enables the participants to report from the short term store, and which was presumably contingent on the completion of the initial selection process. The cue was presented 0, 150, and 300 ms after the target, and was followed by a pattern mask comprising mutilated letters and digits for 50 ms. The mask was presented 200, 300, 400, or 600 ms after the cue. Note that the lowest onset-onset target-mask interval was 300ms. Results showed that the amount of masking depended on the cue-mask interval, rather than the target-mask interval, in keeping with the idea that the mask was affecting the second naming process rather than the initial selection process. They concluded that with a delay in presenting the mask, masking of a higher, more central, cognitive process was possible.

Potter (1976) also postulated two distinct kinds of masking effects, perceptual and conceptual masking, the former affecting perceptual processes, while the latter affect conceptual processes, the assumption being that perceptual processes require the presence of the stimulus itself or the icon, whereas conceptual processes operate on the output of the perceptual processes and transfer information to a more permanent memory store. She tried to identify the stimulus exposure required for participants to identify a picture preceded and followed by a mask (a collage of random shapes and colours). A 120 ms exposure was sufficient for 80% recognition rate. She compared this with another experiment where a 113 ms exposure of sequentially presented pictures secured a recognition rate of 11%, and with an earlier experiment (Potter & Levy, 1969) where the recognition rate was 11% for an exposure of 125 ms. She argued that 100 ms were enough for identification of a picture; and a mask comprising meaningless collage of shapes and colours had no effect on this process; but several hundred milliseconds more of processing was required before memory became immune to masking by a meaningful, conceptually similar picture that followed it in a sequence. Based on such evidence, Potter (1993) proposed a 'very short term conceptual memory' that was distinct from STM (comprising the phonological loop that permits rehearsal). She proposed that CSTM was a dynamic structure building process that was contingent on conceptual representations in LTM, and was in turn, crucial for transfer and retention of current information in LTM.

Potter's idea of conceptual masking was tested by Intraub (1984). Recognition memory for series of pictures each presented for 112 ms was tested, when the 1.5 sec inter-stimulus interval contained a blank field, a familiar repeating picture, a new picture, a new nonsense picture, or a new inverted picture. The maximum disruption of recognition performance occurred when the new pictures were used which showed objects which fell into the same super-ordinate category, such as people or foods, (though not exactly the same object), thus supporting the conceptual masking hypothesis. To compare perceptual and conceptual masking in a single experimental design, Loftus and Ginn (1984) presented a mask immediately after a stimulus picture or after a delay of 300 ms. In an attempt to specify the qualities that might affect perceptual and conceptual masking, they tested the effects of mask luminance and attention demand of a mask. Attention demand was operationalized as a noise mask (low demand) and a photo similar to the target picture, but changing on each trial (high demand). Results established a double dissociation. In the immediate mask condition, a brighter mask was more effective than a dim mask, but attention demand had no effect. Conversely, in the delayed mask condition, mask luminance had no effect, but the photo mask was more effective than a noise mask.

Hollingworth and Henderson (2003) tested whether the inconsistent object advantage (the fact that an inconsistent object in a scene is better detected) had a conceptual locus or whether it derived from the short term memory of the context provided by the scene. Assuming that the pattern mask (comprising overlapping lines, curves and angles) interrupted subsequent perceptual processing of the scene but allowed conceptual processing to continue, whereas the conceptual mask (comprising a line drawing of a different scene) interrupted both perceptual and conceptual processing, they compared if the two kinds of masks had a differential effect on inconsistent object advantage. The results were not different due to the two types of masks. They also contrasted the effect of the pattern mask when presented for 30 ms and 400 ms, thus allowing a greater time for conceptual processing; that too, had no differential effect on the detection of inconsistent vs. consistent objects. Thus they concluded that the inconsistent object advantage did not result from a conceptual locus, but was derived from the contextual information provided by short term memory for the scene.

More recently, masks of the same type presented after different time intervals have been used to study the process of consolidation, i.e. the transfer of information into VWM. Woodman and Vogel (2005) used masks to separate the processes of consolidation and maintenance. They compared a consolidation-baseline condition with a consolidation-during-maintenance condition, hypothesizing that if consolidation and maintenance were drawing on the same resources, then performance would be poorer in the maintenance condition. However, the rate of consolidation remained the same in both conditions. Thus, they asserted that consolidation and maintenance are independent processes. Vogel et al. (2006) used masks at the locations of previously presented stimuli to study the rate of consolidation of coloured squares into VWM. They found the rate of consolidation to be about 50 ms per item and capacity limited to about 4 items.

Indeed masks have been used to interrupt consolidation in WM beyond the visual domain. Saults and Cowan (2007) used both visual and auditory masks to study the central capacity of WM. They argued that if the storage limits of WM are defined by the focus of attention to be 3-4 items, then storage limits should not be modality specific, and should also apply to information from different modalities. Using a change detection task, they presented simultaneously a six square visual array and a 4 digit auditory array for 600 ms, followed by either visual or auditory masks after 0, 400, or 600 ms. The duration of the mask was 600 ms and then a whole display probe followed after 3000 or 4000 ms. Overall, they found that bi-modal capacity did not exceed the unimodal capacity. In fact, it was slightly but not significantly lower than the unimodal capacity for visual items alone. Thus they concluded that the limit of 3-4 items is applicable across domains. The mask presented at 0 ms (600 ms after stimulus onset) did yield lower capacity estimates, indicating that consolidation into WM was reduced by the presentation of the mask.

Sligte et al. (2008) used an energy mask (a uniform, full screen, non-informational flash of light) to disrupt iconic storage, and both an energy mask and a pattern mask to disrupt VSTM. The paradigm they used was a combination of change detection and probe technique in that they presented a cue just after offset of the study display (iconic-cue), 1000 ms after offset of study display but immediately after a mask (retro-cue) or after onset of probe array (post-cue). They found that the energy mask significantly disrupted performance assessed with the iconic-cue, but had no effect with the retro-cue, whereas irrelevant pattern masks disrupted performance with the retro-cue. Nevertheless, this performance was much higher than the performance after the post-cue, which indicated the presence of a high capacity, ‘fragile VSTM’ between iconic memory and the ‘traditional’ more durable VSTM with a capacity of four items.

In the experiments by Sligte et al. (2008) and indeed, in earlier work on perceptual and conceptual masking, the effects of the kind of mask and the timing of the mask are often confounded. Perhaps, it is more accurate to regard the perceptual-conceptual distinction as a single bipolar continuum. In principle, any mask can and probably has both effects, but to different degrees. Energy masking is primarily sensory / perceptual, object substitution masking is largely conceptual, whereas different pattern masks may be placed at different points on this continuum. The mask itself is a multidimensional object and has various properties – luminance, similarity to the target, meaningfulness etc, any or all of which might affect performance on the target. The basic assumption of the masking paradigm is that a target and mask compete for the resources required for the processing ongoing at that time. The perceptual and/or conceptual properties of the mask that have an effect are therefore critically contingent on the time at which the mask is presented, and ultimately on the processes that are taking place at that time.

To fully appreciate the role of time in masking, it is also important to consider the various explanations for the masking effect. The very existence of the masking effect is paradoxical. If a target can be recognised when presented alone for less than 1 ms, why should it become unrecognizable simply because it is followed by a mask? How does the mask act backwards in time to affect the target?

Traditionally, the interruption explanation was favoured for backward masking (Averbach & Coriell, 1961; Haber 1969, 1970; Sperling, 1960, 1963; Turvey, 1973). It was based on the evidence that the iconic image persisted well over 100 ms. But the image could not be recognized or reported from the iconic store, unless it was encoded/ consolidated. This further encoding took time. A mask could disrupt this process, and thus erase the icon at the initial stage, or if presented after a delay, prevent consolidation and read out. Physiologically, the mask interrupted a post sensory central process. It is on the basis of this explanation that a mask is used to study the speed or amount of consolidation into WM (e.g., Vogel et al., 2006; Woodman & Vogel, 2005, 2008; Zhang & Luck, 2008)

The phenomenon of forward masking, however, is difficult to accommodate in the interruption account. So an alternative explanation, the ‘integration’ account, was proposed (Coltheart & Arthur, 1972; Di Lollo, 1980; Eriksen, 1980; Eriksen & Schultz, 1978; Felsten & Wasserman, 1980; Scheerer, 1973). This was based on evidence that the visual system lacks fine temporal resolution. Thus the target and the mask are treated as if they occur simultaneously. Masking occurs because of temporal integration of the two patterns in the visual cortex. More similar the patterns, easier is the integration process, and greater the masking effect. Sequential presentation at short SOAs encourages integration, but very long delays between the target and the mask hamper integration. Physiologically, sensory and early visual processes underlying pattern recognition and the lack of temporal resolution in these processes was held to be the cause of masking.

More recently, concomitant with technological advances in the measurement of processes in the brain, another explanation of masking which is an advance on both the interruption and integration account, has been put forth. This holds that masking interrupts the reentrant processes in the brain, not only when the mask is a four dot mask (Di Lollo et al., 2000), but also when it is a pattern mask (Enns & Oriet, 2007; Fahrenfort, Scholte, & Lamme, 2007). This view accepts that initial sensory processes are not sufficient for distinguishing objects and require confirmation by recurrent processes. The mask interrupts these recurrent processes or interferes with them because it competes with the resources required by the recurrent processes.

Di Lollo et al. (2000) first proposed that interference with reentrant processes was the cause of four-dot masking. Enns and Oriet (2007) proposed that top-down factors in terms of goals and expectancies set up through task instructions affect reentrant processes before the separation of processing in the dorsal and ventral streams, for both these streams begin with using object representations. This speculative hypothesis was formulated on the basis of their study with pattern masks and target objects defined either by colours or by shapes, which showed that target-mask similarity on only task relevant features increased the masking effect; but if the features were irrelevant to the task, masking was not effective. Fahrenfort et al., (2007) also used a pattern mask and EEG measurements to determine what happens in the human visual cortex in masked as well as non masked conditions. Though extrastriate visual areas were activated early on in both conditions, showing that feed-forward processing was preserved, EEG derivatives associated with reentrant processing were absent in the masked condition. That masking competes for resources utilised by cognitive processes and can act as an interfering mechanism is also substantiated by physiological evidence showing that TMS interferes with visual processing and causes reduced performance similar to visual masking with the maximum effect for SOAs of 80-100 ms (Amassian, Cracco, Maccabee, Cracco, Rudell, & Eberle, 1989; Kammer, 2007).

In the present research, assuming that the timing of the mask is the crucial variable, a single type of mask was created to have both perceptual and conceptual masking properties. The mask was created by splitting each of the 36 stimuli used in the experiment into four parts, and then randomly splashing these 144 images on a rectangular area larger than the one occupied by the stimuli by 3 pixels on all sides. Thus the mask covered virtually the same area covered by the stimuli, and was identical in brightness and the hues used. It was also decided that the contents of the mask would be randomized for every trial, so that there is no relation whatsoever to the targets as well as the previously presented masks. If the contents of the backward mask are related to previously attended stimuli presented as a pre-mask, the backward mask is considerably less effective, an effect called repeated mask reduction (Drew & Vogel, 2008).

This mask was presented immediately after the study display in one experiment, and after a delay of 300 ms in the other experiment, to assess its effect on performance. Experiment 8 essentially replicated experiments 1, 2, and 5 and established the baseline against which performance in the masking experiments was compared. It was hypothesized that the immediate mask in Experiment 9 would obliterate the effects of iconic memory in performance, and reduce the gap between the unchanged location and random locations conditions at the initial study-test interval of 100 ms. The delayed mask in Experiment 10 presented 300 ms after study-display offset was also hypothesized to reduce the gap between the unchanged and random locations conditions, but because it interfered with the processes of consolidation and inhibition happening at that time. These hypotheses, the experiments done to test them, and the results are discussed in detail in Chapter 7.

Entering the Storage Space

Chapter 8 reports the final experiments done to test the factors attendant at the time of encoding in the results of the previous experiments. In Experiment 11, the exposure time of the study display was increased to test whether it would differentially affect performance at the short and long study-test intervals. Increasing the study-display duration should generally improve performance though Busey and Loftus (1994) and Loftus and Maclean (1999) have empirically shown that there is a threshold before performance can 'liftoff' and there is a duration at which it reaches an asymptote. Pashler (1988) found a small but significant increase in performance in a change detection paradigm studying memory for 10 letters as the study display was shown for 100, 300, and 500 ms, with the test display presented after 67 ms in each case. Liu and Jiang (2005) asked participants to remember objects in scene images to find that 250 ms allows only about one object to be retained in memory whereas about five objects and many more details about the scene could be remembered if participants were allowed to take as much time as they liked. In the latter condition the mean time taken by the participants was 16 seconds. The time based resource sharing model (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet & Camos, 2007) assumes that attention, a limited resource, is required for both processing and maintenance in WM. Even maintaining the goal set or task instruction while performing the processes required for task fulfilment can be attention demanding. The central bottleneck is serial and allows only one process at a time. Dual tasks can be successfully performed only by rapidly and frequently switching attention back and forth. Thus if there is no time constraint, all tasks can be performed with relative ease. Conversely, even simple tasks can become demanding if they are time limited. Cognitive load is thus determined by the duration of attention demanded. Portrat, Barrouillet, and Camos (2008) have shown that decay in WM is also time based. The model is not an alternative to established models of WM, it simply urges that time be considered as a factor in the deployment of central resources presumably required to complete any task. With regard to the present experiments, all this evidence predicts that increasing the exposure durations would ensure better performance. Nevertheless, the primary motive for this manipulation was to study whether increasing the study-display duration would have any differential effect on the performance of the participants in the unchanged and randomized conditions at the different study-test intervals. The rationale and the associated hypotheses are given in Chapter 8.

Another perceptual factor that might have influenced the results was configural encoding. The experiments with masks had demonstrated the effects of iconic memory, but it was desirable to further test the effect of disrupting configural factors at the time of encoding itself. Sequential presentation of stimuli has often been used with the logic that it prevents perceptual grouping and/or configural encoding (e.g., Alvarez & Cavanagh, 2008; Woodman & Luck, 2004). In so far as the participants' performance is contingent on configural encoding, sequential presentation would affect performance. If performance is aided by configural encoding, as presumably it is in the unchanged locations condition, sequential presentation should disrupt performance. If performance is hindered by configural encoding, as it might be in the random locations condition then sequential presentation should improve performance.

An important issue to consider is that sequential presentation also provides an additional code for remembering stimuli. Sequential viewing allows attention to be exclusively focussed on the object presented and this may lead to better performance. Yamamoto and Shelton (2009) investigated memory for room sized spatial layouts. Sequential viewing of objects in this context led to performance that was similar or superior to simultaneous viewing. This performance was maintained when viewing was directed sequentially, though objects were presented simultaneously. Thus, the conclusion was that sequential presentation gained from the deployment of focal attention to the locations of particular objects. On the other hand, Mackworth (1962) suggested that the functioning of attention in simultaneous and sequential presentation might favour simultaneous presentation because simultaneous presentation allows voluntary and flexible allocation of spatial attention, and if sufficient time is allowed, rescanning is also possible. In contrast, sequential presentation imposes the order of encoding and precludes rescanning, particularly if the previous stimulus vanishes as the next one is presented. This would suggest that simultaneous presentation should result in superior performance as compared to sequential presentation when sequential presentation does not allow rescanning.

Thus two experiments with different types of sequential presentation were designed. In Experiment 12, stimuli were presented one by one as the study display was gradually built up. In Experiment 13, the stimuli were presented one by one such that the first one vanished as the next was presented. Both experiments could be contrasted with the performance in Experiment 11, which used simultaneous presentation of stimuli.

Empirically, distinctions in performance have not been easily or regularly obtained when stimulus presentation is directly contrasted in terms of simultaneous vs. sequential. In an early study, Igel and Harvey (1991) studied the accuracy of reconstruction of 1 to 10 locations presented simultaneously or sequentially, with similar results up to six locations. In the sequential condition errors increased gradually with an increase in set size. In the simultaneous condition, errors increased up to six locations, but thereafter there was no change in errors made, despite the stimuli increasing up to 10. They reasoned that stimuli up to six were encoded serially even in the simultaneous condition, but more stimuli afforded a chance of configural encoding and thus aided performance in the simultaneous condition. This was not possible in the sequential condition, and hence performance was poorer for the sequential condition after six stimuli.

Zimmer, Speiser, and Seidler (2003) postulated that a rehearsal process termed ‘spatial marking’ is required to maintain the link between spatial locations and temporal order in the Corsi block test. However, in their experiment, concurrent tapping reduced performance to the same extent whether memory was tested for locations or temporal order. Their explanation was that the sequential order was being remembered by the participants whether or not they were asked to do so. Dent and Smyth (2006) did find differential performance effects, but again differences emerged only under high cognitive load with set sizes beyond capacity. They argued that up to 3 locations are remembered independently, whereas 6 to 10 locations are subjected to a configural representation. This being more difficult for sequential presentation, differences between mode of presentation favour simultaneous presentation at larger set sizes. Such evidence can also be interpreted to indicate that cognitive load which presumably increases with set size, is a significant factor in the difference between simultaneous and sequential presentation. Thus, it may be argued that the similarity of performance between simultaneous and sequential conditions is maintained by devoting more cognitive resources to the sequential task, but when these resources are taxed in a high cognitive load condition, performance suffers.

Fisk and Sharp (2003) had first demonstrated the involvement of central executive in visuo-spatial memory using a running memory span task with visuo-spatial sequences. Specifically 4 to 10 cells were highlighted in a sequence on each trial, with the length unknown to the participant. Their task was to report the last four cells in serial order. Thus they needed to constantly update their memory, presumably utilising executive memory resources. This was confirmed by the finding that using random generation in a dual task procedure significantly reduced performance. However, in contrast to results in running memory span tasks with verbal sequences, the effect of random generation did not vary with increasing list length. In fact, it reduced the primacy effect by reducing the recall of early serial positions.

Lecerf and De Ribaupierre (2005) studied the effect of simultaneous vs. sequential presentation using a 6×6 matrix, 2-7 cells of which were coloured white either simultaneously or sequentially in a random or ordered way. Three kinds of memory tests were used across experiments, though all required participants to say same or different. On different trials, one cell was displaced either in a whole display probe or a single cell probe, or the whole pattern was displaced, though the relative positions of the cells remained the same. Thus the experiments tested the role of extra-figural encoding, intra-figural pattern encoding, and spatial path encoding. Performance was best in the simultaneous condition whether a whole display probe or single cell probe was used, probably because while all three types of encoding are possible with simultaneous presentation, sequential presentation does not allow pattern encoding. Ordered sequential presentation was better than random sequential presentation, as it allowed path encoding. Simultaneous presentation lost its advantage only in the third experiment when the whole display, displaced probe was used to test memory. Across experiments, performance decreased with increasing set size, and attention/perceptual factors were also clearly relevant.

Rudkin, Pearson, and Logie (2007) studied the difference between simultaneous vs. sequential presentation testing performance on the Matrix Patterns and Corsi Block tests. They used the dual task procedure using tasks highly demanding of central executive resources, random digit generation, and random interval repetition, as the second task. Results showed greater involvement of executive resources in the sequential rather than simultaneous task performance. However, in these experiments, sequential presentation was linked with the requirement to recall sequential order, whereas simultaneous presentation did not require retention of serial order. Darling et al. (2009) directly compared simultaneous and sequential presentation and tested the memory for appearance or location of items with no requirement for the participants to retain serial order. Mode of presentation had no differential effect on performance, nor did it interact with any of the secondary tasks in the dual task conditions. Comparing the evidence from these two studies, it seems that it is not the mode of presentation *per se*, but the retention and retrieval of serial order which draws on executive resources.

Mode of presentation, however, does seem to be more important in feature binding. Allen et al. (2006) reported significantly lower accuracy for remembering bindings with sequential as compared to simultaneous presentation, even with a single item probe which did not require reproduction of serial order. It is important to note that sequential presentation in their experiment comprised four stimuli, each presented for 250 ms and each followed by a 250 ms blank interval, whereas simultaneous presentation comprised all four stimuli presented for 250 ms in all. Presumably, this was done because the rationale for the experiment was to study the fragility of bindings in comparison to single features. This paradigm, however, not only increased the exposure for each separate stimulus, but the blank intervals might have made it more difficult to remember the stimuli as a whole pattern, whereas the whole pattern might have been remembered in the simultaneous presentation condition. Furthermore, the set size was well within capacity of VWM, and did not tax attentional resources.

Fougnie and Marois (2009) tested memory for colour-shape bindings using a single probe and gave an attention demanding multiple object tracking task during the retention interval. In one experiment, the initial display presented all stimuli simultaneously, whereas in another experiment they were presented sequentially in the same location (at fixation). Greater interference from the tracking task was observed for the binding condition as compared to the single feature conditions in both experiments, but it was much more in the simultaneous presentation experiment than in the sequential presentation experiment. Note that the display comprising three items was shown for 400 ms, and the probe was given after 6800 ms (nearly 7 seconds) later.

As mentioned earlier, the experiments with sequential presentation (Experiments 12 and 13) were done essentially to study the effect of disrupting the encoding of bindings on the pattern of results observed in the earlier experiments. In so far as performance was affected by configural encoding, it was expected that the pattern of results would differ in these experiments as compared to the baseline Experiment 11 which used simultaneous presentation. The alternative hypotheses are clearly delineated in Chapter 8.

Dwelling on the abode

Given that the stimuli in experiments 12 and 13 were presented sequentially, they also yielded an opportunity to study serial position effects in the results. The serial position effect is the empirical observation that the initial and the final items presented in a series are better retrieved than the items in the middle positions.

Primacy refers to better retrieval of the first few items, whereas recency refers to better recall of the last few items in a series.

The initial explanation for the primacy effect was that the first few items entered LTM and were retrieved from there, whereas the last few items showing the recency effect were retrieved from the STM. The primacy effect thus was held to be proof of the existence of LTM. Hardly anybody disputes the actuality of LTM, nevertheless, alternative explanations of the primacy effect have been offered. Covert rehearsal is one process which might explain the primacy effect. When participants are asked to rehearse aloud, they produce the first few items more often than any others (Rundus, 1971; Tan & Ward, 2000). Thus, the primacy effect is a kind of recency effect, in the sense that the participants represent the initial items to themselves instead of focussing on the last few items presented by the experimenter (Ward, Tan, & Bhatarah, 2009). In such conditions of rehearsal, a negative recency effect is also observed, whereby recall is weaker for the last few items as compared to the initial or middle items, and in contrast to the robust recency effect usually observed (Craik, Gardiner, & Watkins, 1970). Rehearsal helps to form a stable representation, but the last few items suffer because they were neither rehearsed (and so did not achieve a stable representation), nor can they be retrieved from primary memory. Note that rehearsal alone cannot explain why primacy and recency occur together.

In contrast to these studies for verbal items, in the visuo-spatial domain, when immediate serial recall was assessed for sequentially presented dots, and eye movements were recorded as measures of overt rehearsal during presentation and afterwards during the retention interval, it was found that though rehearsal increased the overall recall performance, it had no differential effect on the serial position curves that were obtained, showing both primacy and recency effects (Tremblay, Saint-Aubin, & Jalbert, 2006). This study suggests that rehearsal may not be a significant factor in retention according to serial positions in the visuo-spatial domain.

Another factor influencing primacy is distinctiveness. The primacy effect is markedly reduced if the items are crowded, i.e., they are presented at a faster rate. This lack of primacy is explained by lack of distinctiveness of earlier items. In keeping with this idea, in the domain of VWM, Phillips and Christie (1977) noted that an increased rate of presentation had no effect on the single item recency effect they found, but it had a significant negative effect on the 'stable component' of the serial position curve, thus reducing the recall of the first few matrices in the series.

The recency effect was initially cited as the strongest evidence for the existence of STM. The effect was exterminated by a filled delay of even a few seconds irrespective of whether the material presented during the delay was similar or different to the material to be remembered (Glanzer & Cunitz, 1966), and if instructions were to begin recall from the beginning of the list (Dalezman, 1976). Recency effect was found in amnesic patients who had virtually no LTM, (Baddeley & Warrington, 1970) and was absent in patients with reduced STM (Shallice & Warrington, 1970). Soon, however, studies began to emerge which showed that the recency effect was not limited to STM. Tzeng (1973) and Bjork and Whitten (1974) used a continuous distracter free recall paradigm to show that if the items to be recalled were each separated by a filled delay, the recency effect was not eradicated by presenting a filled delay afterwards, in contradiction to Glanzer and Cunitz (1966). Baddeley and Hitch (1977) found a recency effect extending over several weeks when they tested the recall of rugby players asking them the names of teams against whom they had played.

It is now agreed that the recency effect can be manifest in any memory system and is a generally robust phenomenon (Baddeley, 1998, Nairne, 2002). Baddeley (2007) holds that the constant ratio rule describes the recency effect precisely, "Over a wide range of situations extending from seconds to years, the probability of recalling a given item is a constant function of two variables, the temporal distance between that item and its nearest competitor (Δt) divided by the interval between item presentation and test (t). This is termed the discrimination ratio, and has been demonstrated to hold constant under a very wide range of circumstances. With immediate recall, this favours the more recent items, an advantage that is eroded as recall is delayed" (Baddeley, 2007, p.104). This was first proposed and tested as a hypothesis by Hitch, Rejman, and Turner (1980) as well as Glenberg et al. (1980) using the continuous distracter technique. Clearly, the recency effect does not occur simply because the interval between presentation and test is very short. Temporal distance from other competitors of the item is also a factor. But as McGeoch (1932) famously stated, time per se can have no effect, and so one needs to look closely at why recency occurs.

Baddeley (1976) suggested that retrieval from memory involved two stages, accessing a general cluster of memory traces, and then discriminating among them. Longer delays might lead to greater trace decay, or more noise in the system, or 'general interference' (Baddeley, 2007, p.109), and thus make specific memories less distinct. Though this suggests that the recency effect would vanish at longer delays, if this argument is reversed and stretched, it also implies that the recency effect might be obliterated at even very short delays if the interval between presentation and test is a filled interval and thus involves interference (whether due to similar or different material). This is exactly what Glanzer and Cunitz (1966) found. To a large extent, Baddeley's explanation of the recency effect is in terms of interference at the time of storage and retrieval. Both proactive interference from within-list previous items as well as retroactive interference from subsequent material presented are relevant factors.

A more complex explanation was proposed by Baddeley and Hitch (1977, 1993). Besides decay and interference, it involves priming of presented items, limited capacity of activation, and hence strategic retrieval of most readily accessible items. To use an analogy, suppose one is lighting a series of candles. A sudden draught of air through the door blows them out. The task is to light the candles again. Once a candle is lit it is easier to light it again as compared to ones that were never lit; and out of all the candles which were lit, it is easiest to light the last one, because it still retains heat. Analogously, the process of encoding, results in the priming (activation) of those items, such that they are easier to reactivate. Since the total capacity of activation within WM is limited, as each successive item is presented, the activation level of previous items is reduced. The recency effect occurs due to a retrieval strategy that uses the fact that the most recently presented items retain their level of activation, and are thus most easily accessible. The priming of encoded items is passive and automatic, but the recency effect is the result of an active strategy that may or may not be used.

More advanced models to explain the serial position effect, and the results of various experimental manipulations, have also been proposed. The basic aim of these models has been to explain how the serial order of any sequence is encoded. Across models, rehearsal is conceptualized as repeated retrieval. This confluence is well-expressed in a recent review article as, “rehearsal is simply a controlled sequence of retrievals and re-encodings of items into the focus of attention” (Jonides, Lewis, Nee, Lustig, Berman, & Moore, 2008, p.206). Almost all models also agree on competitive queuing, the mechanism that dictates that the most strongly activated item is selected for retrieval, and is inhibited immediately thereafter to enable the retrieval of the next strongly activated item, and then slowly recovers from inhibition. This mechanism is also supported by the fact that participants often fail to remember a repeated item (Jahnke, 1969). In fact, suppressing previous responses seems to be a general process in sequential behaviour (Houghton & Tipper, 1996). It also makes logical sense because otherwise the participant would never get away from the first response, that being the most potent one!

The difference between the models largely rests on how they conceptualise the items are encoded in the first place. Many experiments have confirmed distinctions between memory for items and memory for order (review by Marshuetz, 2005). Items are encoded faster than information about their order (McElree & Dosher, 1993), recognising an item is much easier than recalling the next item when probed (Sternberg, 1967), and order information is lost faster than item information (Bjork & Healy, 1974). Irrelevant speech, articulatory suppression, and concurrent finger tapping impair order memory more than item memory, whereas temporal grouping improves order memory more than item memory (Henson, Hartley, Burgess, Hitch & Flude, 2003).

Returning to a comparison of models on this issue, many of them hold that items are encoded separately from the order in which they are presented. The order of the items is thus not a property of the items themselves, and order information is provided autonomously by an evolving context signal (Burgess & Hitch, 1999, 2005, 2006), or a temporal signal from an oscillator (Brown, Preece, & Hulme, 2000), or by positional markers (Henson, 1998). In contrast, other models emphasize that order information is inherent in the items themselves, the first item being encoded most strongly, the second less so, the third even lesser, and so on, with the last item being with the weakest encoding strength. For instance, the primacy model (Page & Norris, 1998) proposes that serial order is coded by associating each successive item with the first item presented, but with decreasing strength. This generates the primacy gradient, for the quality of information available for retrieval decreases across serial positions. In addition to competitive queuing, the primacy gradient is held to be sufficient to generate the serial position curve in simple forward recall. Farrell and Lewandowsky (2002) adhered to a similar idea, though in their recent C-SOB model, Lewandowsky and Farrell (2008) have included a context marker. Testing whether order memory is driven by a temporal signal, Farrell (2008) found that instructing participants to group the digits had similar effects on recall of order and recall of timing, the timing of recall mirrored the timing of input, and temporally isolated items were better recalled. The exception to the dichotomy between the models (which propose a separate source of order information and which say that it inheres in items themselves), is OSCAR (Brown et al., 2000) which uses the primacy gradient as well as an oscillator.

Though the aim of these models has been to explain the retention of the serial order, many of them focus on, and are able to explain, only one part of the serial position curve, either the primacy or the recency part. One notable exception is the start end model (SEM) that incorporates both a primacy and recency gradient (Henson, 1998). SEM assumes that the position of each item in the list is dual coded by a start marker and an end marker. The start marker is strongest at start of a sequence, and decreases in strength towards the end, resulting in the primacy gradient. The end marker is weakest in the beginning, but gradually grows in strength. Thus, just as an item in a plane is coded in relation to the length and breadth of the plane, the relative strengths of the start and end markers provide a two-dimensional code for each position in a sequence. Further, each item is coded as an episodic token in short term memory, all tokens being unordered. The ordering occurs at the time of retrieval with the help of positional cues. For any token to be retrieved successfully, it must win not only against other tokens but also against long term memory representations.

Another recent model that uses evidence from the serial position curve to reiterate the dual store model insists on two memory components: an episodic contextual system with changing context, and an activation based short term memory buffer that drives the encoding of item-context associations (Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Davelaar, Usher, Haarmann, & Goshen-Gottstein, 2008; Usher, Davelaar, Haarmann, & Goshen-Gottstein, 2008). Two key predictions of their model, validated through simulations as well as empirical studies are: first, dissociation between long term and short term recency due to proactive interference, and second, shift from recency to primacy with an increased rate of presentation. They hold that long term recency is due to contextual retrieval based mechanisms which are susceptible to proactive interference, whereas short term recency is the result of unloading the content of the activation buffer which is immune to proactive interference. The shift from recency to primacy with increased rate of presentation arises from the internal dynamics of the activation buffer. At slow rates of presentation, each new item accumulates enough activation for self-support, and to overcome inhibition from previous items, so early items are more easily displaced, and recency ensues. At faster rates of presentation, however, later items do not have enough activation to overcome competition from previous items and a primacy effect is shown with a corresponding lack of recency.

All the models discussed heretofore have been proposed based on studies with verbal material. In comparison to the countless studies in the verbal domain, very few researchers have explored whether similar mechanisms may be involved in the domain of visuo-spatial memory. In fact, the serial position effect itself is not always obtained with sequences of visually presented non-verbal items. Tydgat and Grainger (2009) explored the form of the serial position curve in the identification of letters, digits, and symbols, to find that the end position advantage was greater for letters and digits than for symbols. The multiple component view of WM that the phonological loop and the visuo-spatial sketchpad are independent systems accommodates the idea that different factors might operate across these domains in the retention of sequences. In fact, the visuo-spatial sketchpad has been further bifurcated into the visual and spatial systems with the tasks assessing each being respectively simultaneous and sequential (Della Sala, Gray, Baddeley, & Wilson 1999; Logie & Marchetti, 1991).

Early on, Phillips and Christie (1977) tested recognition memory for sequences formed by lighting up randomly selected cells in a 4 × 4 matrix. A single item recency effect was obtained irrespective of whether participants were tested in a reversed presentation order of all stimulus sequences, or were probed by a single stimulus sequence; whether or not stimuli were masked; and for stimulus sequences of different lengths. This effect however, vanished when a simple five digit adding task followed the last item. They also found that an increase in presentation rate decreased performance in the early sequential positions (1-4), thus affecting the 'stable component' of the serial position curve, but had no effect on the one item recency noted in the experiment. Notably, they did not observe a bow shaped serial position curve. Rather, they found a flat gradient for the earlier items, and one-item recency, probably because of the complexity of the stimuli used.

Jones, Farrand, Stuart, and Morris (1995) did find bow-shaped serial position curves with a simpler task testing memory for the spatial position of a sequence of dots. For the recall test, all the spatial positions were displayed and the subject had to recall the sequence by pointing to the spatial positions. They also observed an increase in error with increasing list length. Avons (1998) noted the fact that serial report yielded serial position curves in Jones et al. (1995) study and applied the recall method to

6×6 block matrix patterns with half the cells filled. The patterns were presented sequentially, each for 1.55 secs with blank intervals of 0.46 secs. The test phase involved simultaneous presentation of all patterns, with the participant required to indicate the serial order in which the matrices had been presented. Results showed markedly bowed serial position curves, for sequences of 4, 5, and 6 matrices. Articulatory suppression, and concurrent tapping, reduced performance, but had no effect on the shape of the serial position curve. However, when tested using two-choice item recognition, a flat gradient was obtained with no primacy or recency. Consequently, Avons (1998) concluded that the form of the serial position curve for visual patterns depended on the task used to assess memory. Ward, Avons, and Melling (2005) investigated item and order memory for sequences of seen unfamiliar faces and heard non-words. Results showed bowed serial position curves with faces as well as non-words, when the task was serial reconstruction of order. However, when a two-alternative forced choice test of item recognition was used, limited recency, no primacy, and above chance performance on all items was found. Since the results were similar across visual and auditory modalities but different for the tasks used, it was reiterated that serial position functions were task rather than modality dependent.

Tremblay, Parmentier, Guerard, Nicholls and Jones (2006) used an order reconstruction task and in a single experiment with a repeated measures design, compared auditory-spatial, auditory-verbal, visual-spatial, and visual-verbal stimuli. Strikingly similar serial position curves with primacy as well as recency effect were obtained. In keeping with the modality effect, recency was stronger for auditory than visual presentation for spatial as well as verbal stimuli. Lewandowsky, Brown, and Thomas (2009) also used an unconstrained reconstruction task with consonants as stimuli (but with articulatory suppression, thus consonants being akin to recognizable shapes). They found a recency effect in immediate but not delayed reconstruction, and tendencies to recall temporally isolated items first, to recall in forward order, and for output orders that minimized travel through memory space.

Smyth, Hay, Hitch, and Horton (2005) presented sequences of faces followed by a complete set for reconstruction of the sequence in serial order. Analogous to studies with verbal material, they found a substantial primacy effect, one-item recency, errors mainly limited to adjacent serial positions, and a visual similarity effect. Serial position effects were found when faces had been seen for as little as 300 ms and after a 6-second retention interval filled with articulatory suppression. Articulatory suppression did not interact with the serial position effect or with the similarity effect. Thus, they reasoned that although serial position effects found with unfamiliar faces are not based on verbal encoding strategies, memory for serial order may be general across modalities. Hay, Smyth, Hitch, and Horton (2007) also confirmed that verbal encoding does not affect memory for faces, as verbal suppression did not have any effect on overall performance or the shape of the serial position curve. Hurlstone, Hitch, and Baddeley (2009) used evidence from transposition latencies to show that analogous to results obtained with verbal sequences; visuo-spatial sequences are also coded by a primacy gradient coupled with positional markers.

More recently, Johnson and Miles (2009a, 2009b) have studied the serial position curve across modalities. Johnson and Miles (2009a) tested whether the serial position function is task, rather than modality dependent. The same non-word sequences, presented either visually or orally, tested with a two alternative forced choice paradigm, produced similar serial position functions. Forward testing produced a flat serial position function, while backward testing produced two-item recency in the absence of primacy. This result was found with and without articulatory suppression at the time of encoding. However, the observation of two-item recency contradicted the single-item recency observed for backward recognition testing of visual stimuli (Phillips & Christie, 1977). Johnson and Miles (2009b) compared lists of sequentially presented odours, unfamiliar faces, and pure tones. Employing single-probe serial position recall and following a correction for a response bias, qualitatively different serial position functions were observed across stimuli. Odours produced an absence of serial position effects, unfamiliar faces produced both primacy and recency, and pure tones produced recency but not primacy. The authors support the modular conceptualization of short-term memory, but also note that the results can be explained by the SIMPLE model on the basis of differences in distinctiveness across the various sense modalities (Brown, Neath, & Chater, 2007, 2008).

As is evident from above, in domains other than verbal memory, interest in memory for serial order is at the stage where similarities and differences in the serial position effects found in various domains and tasks have been noted, but formal models and theories explaining the effect, and making contrasting predictions to be tested, are yet to be proposed. Analogous to the ideas in the verbal domain one may speculate that serial order might inhere in the items themselves, or alternatively, serial order may be separate from item information, and might be controlled by a mechanism, which is agnostic with regard to the kind of material it operates on. Saito, Logie, Morita, and Law (2008) confirmed the differences between visual and verbal WM by showing differential impact of phonological similarity on the recall of Kanji characters, but obtained remarkably similar serial position curves in each domain. Thus they affirm that any memory system which stores serial order will generate a serial position curve.

Burgess and Hitch (2006) speculate that the context/timing signal in their revised model is not specific to the verbal domain and works in the non-verbal domain as well. Significantly, Burgess and Hitch (2005, 2006) also extend their model to LTM, by emphasizing that the connection of each item to the context signal that provides order information in their model is capable not only of large decay over the short term, but also small incremental long term modification. This implies that the encoding of any item can influence connections to the context signal independently in short-term and long-term memory. In contrast to Henson (1998), who postulates that LTM affects only the retrieval stage, Burgess and Hitch (2005) posit a link with LTM at the time of encoding. Burgess and Hitch (2006) explicitly state that context signals are agnostic to the traditional distinction between STM and LTM, and play an important role in the transition of information from STM and LTM, in keeping with the idea of an episodic buffer (Baddeley, 2000).

The activation of LTM representations in the early process of binding is, however, a matter of debate. Certainly, evidence regarding implicit processing of sensory input, especially in patients with unilateral spatial neglect, shows that LTM can affect current behaviour, without any ‘active’ processing in WM. Such patients indicate a preference for good over bad (e.g. an intact house rather than a burning one, an intact banknote rather than a torn one, or an intact wine glass rather than one with a broken rim). This preference is observed despite the fact that they cannot ‘see’ any differences between the images of the two objects, as that they are unaware of the stimuli in one-half of the perceptual field (Bisiach & Rusconi, 1990; Cantagallo & Della Sala, 1998; Marshall & Halligan, 1988).

Nevertheless, most versions of the gateway model, including the multiple component model (Baddeley, 2000; Baddeley & Hitch, 1974) assume that sensory input cannot activate representations in LTM, except through WM. In contrast, Cowan (1995, 1999, 2005) believes that the focus of attention, which would host bound objects, with a capacity limit of four items is simply an activated portion of LTM and thus is embedded within LTM. With a similar logic as Logie (1995), Cowan (2005) points out that sensory memory must have some contact with LTM before information can be passed on to the STM because some sort of categorization must precede encoding of information as objects. Second, even unattended, irrelevant information that enters sensory memory remains in an attenuated form (Cherry, 1953), possibly for comparison with new stimulation. If it is not attended, it cannot be a part of the short term store which is delimited by the focus of attention. Thus, it must be stored in LTM directly. This view implies that items would have activation levels according to the LTM representation that they evoke, and not necessarily according to their input sequence.

Activated representations of LTM are one important source of information that may be manipulated in WM as a workspace (Logie, 1995, 2003; Logie & Della Sala, 2005). Indeed, this model emphasizes that activation of a knowledge base occurs *before* stimulation reaches the workspace that is WM. Whereas the gateway model assumes that raw sensory information is ascribed meaning and interpretation by processes in WM, the workspace model asserts that "the meaning that arises from object identification through perception becomes part of the mental representation held in WM" (Logie & Della Sala, 2005, p.97). Further processing in the workspace is primarily in terms of manipulation of these representations, presumably to fulfil the demands of the task at hand. Thus, the workspace model revises the textbook notion of WM as a gateway, to hold that the sensory input is perceived in the light of the long term knowledge base, and it is the result of this interface that enters WM. Yet, it is not as extreme a view as Cowans' in amalgamating separate stores. Further, it emphasizes presentation sequence in the encoding of items. Indeed, Saito et al. (2008) explicitly propose that any system, which stores a serial order will generate a serial position curve.

As mentioned at the beginning of this section, the two experiments with sequential presentation, Experiment 12 and 13, made it possible to explore serial position effects. Experiment 14 was a partial replication of Experiment 13. If no serial position effects are obtained, it would show that stimuli were processed in a manner similar to simultaneous presentation, with the participants either remembering the whole pattern with the sequential presentation, or focussing on a selected few one by one in simultaneous presentation. If only a primacy effect is shown, rehearsal would be an adequate explanation. If only the recency effect is shown, it would imply that the stimuli in the beginning of the sequence are overwritten by the last or last few stimuli. If both primacy and recency are shown, it would show that stimuli are activated and encoded in the context of their serial position in a sequence. This would be important considering that automatic, instantaneous bindings are usually considered transient and extremely fragile representations. In contrast, activation in a context would suggest links to more stable representations, in a way completing the journey of stimuli that started from input as a multidimensional representation, and reiterating the emergence of a coherent stable object.

RECAPITULATION

As a recap of the debates and key points that emerge from the foregoing review of literature, consider the following:

1. At the physiological level, there is a discernible shift in the conceptualization of binding, from an instantaneous but transient integration of features reliant on synchrony or conjunctively coded neurons, to a process that is initiated by feed-forward processes, but is heavily contingent on recurrent processes.

2. On the psychological plane, there is a debate regarding the role of bottom-up and top-down factors in the process of binding, with some theorists emphasizing the role of the different features in binding, particularly location, whilst others propose that the relevance of features to task goals is the factor of overriding importance. This inevitably implies a guiding role for Working Memory as it is the arena for online processing to achieve extant goals.

3. The role of attention in the binding process is also a contentious issue, with some researchers holding that attention has no special role in binding, while others proposing that it is the major factor in binding. The review indicates that attention itself is of many kinds, and these myriad types may have different roles to play in the process of binding.

4. Two ongoing processes, consolidation and inhibition, are seemingly important in the process of binding. The relative importance of each process remains to be assessed. More importantly, it is important to investigate the nature of these processes by studying the extent of their reliance on representations in memory.

5. It is also important to consider the role of stored representations in the process of binding, particularly those in iconic memory as well as those in VSTM. It is of primary interest to assess whether the transfer of information from the iconic register to VSTM happens in an all or none fashion, or if it is

> a selective process, based on transfer of relevant features and ignoring the irrelevant ones.

To preview the experiments to be reported in this work, Chapter 4 reports the initial pilot Experiment 1 which studied the effect of unchanged and random locations on detection of shape-colour bindings. The study-test intervals used were 0, 200, 1500, 2800, and 4100 ms. Chapter 5 reports Experiments, 2, 3, and 4, which studied the effects of randomizing location, shape, and colour respectively on detection of shape-colour, location-colour, and location-shape bindings for six study-test intervals ranging from 0 – 2500 ms, changing in steps of 500 ms. Chapter 6 reports Experiments 5, 6, and 7 which differed from 2, 3, and 4 only in that the study-test intervals were presented in a random order rather than in blocks as they were in Experiments 2, 3, and 4. Chapter 7 reports Experiments 8, 9, and 10, Experiment 8 being a replication of experiments 1, 2, and 5 in that it tested the effect of randomizing locations on the detection of shape-colour bindings for study-test intervals ranging from 0 to 2500 ms, but all conditions in the experiment were randomly mixed and presented to the participants. It was also the baseline experiment for Experiment 9, which used an immediate mask after the study display, and Experiment 10, which used a delayed mask 300 ms after the study display. Chapter 8 reports Experiments 11, 12, 13, and 14. Experiment 11 tested the effect of increasing the duration of the study display with simultaneous presentation of stimuli, on the detection of shape-colour bindings for the study-test intervals of 0 and 2000 ms, whilst locations were unchanged and randomized. Experiments 12 and 13 differed from Experiment 11 only in that they used sequential presentation, the study display being gradually built up as the items were presented one by one in Experiment 12, while in Experiment 13, the sequential presentation was such that the first item vanished as the next one was presented. Experiment 14 was a partial replication of Experiment 13.

CHAPTER 3

METHODOLOGICAL CONSIDERATIONS

THE TASK: SWAP DETECTION

Myriad methods have been used to assess the process of binding. Researchers aiming to uncover the physiological bases of the process of binding use methods such as EEGs, MEGs, fMRI, and PET scans to study binding. Those who seek to understand binding at the molar level of cognitive behaviour and focus on the factors affecting this process have often used variants of change detection as the experimental task.

The change detection task presents two visual displays to the participant who has to decide whether there is a change in the two displays. The first is the study display, which the participants have to memorise. In the intervening period either a masking or blank display of varying study-test intervals is presented. Then the second display, i.e., the test display is presented, which is the same as the first one, or slightly different. The difference happens to the target stimuli, and the rest are known as the distracters. The varieties of this archetypal description and their implications have been extensively reviewed by Rensink (2002).

Hyun, Woodman, Vogel, Hollingworth, and Luck (2009) have suggested that the detection of difference in a change detection task which requires comparison and response to arrays is similar to a visual search task that requires the detection of a target defined by a simple feature among many distracters. They contend that the detection of change is related to overt and covert shifts of attention analogous to what happens in target detection in visual search tasks. However, the detection of change is not directly related to the manual response, the way a single feature in a visual search task is related to the manual response. They propose that a limited capacity intervening process of ‘consideration’ occurs before the manual response can be given in a change detection task, and the response is consequently delayed.

Nevertheless, it needs to be recognised that the change detection task requires not only the formation of mental representations, but also the maintenance or storage of these representations across time so that they can be compared in successive frames. The task is a perceptual as well as a memory task, and in this sense, particularly suited to the present research, for it yields a single dependent measure of the differences between these two processes. Simply by manipulating the study-test interval one can change it from a test of perception to a test of memory.

Change detection, though, provides only the general rubric for the task used in the present research. Generally, the difference in the change detection task, if it occurs, may be in terms of the addition of a new stimulus, deletion of an old one, or a swap in the already presented stimuli. The present research uses only the last kind of change, a swap between two stimuli. This task was introduced by Wheeler and Treisman (2002) specifically to study bindings. It is not possible to perform this task by remembering which features were presented, for all the same features appear in the study as well as the test display. It is essential to remember how the features were combined to find which ones swapped. Alvarez and Thompson (2009) have used the term 'feature switch detection' to describe this task. Their work has also shown that though this task underestimates the binding capacity of VWM, it is an efficient paradigm for studying the factors affecting the fragile nature of bindings.

The stimuli in the present research are defined by three features: location, colour, and shape. Three features were necessary so that one feature could either remain unchanged or rendered irrelevant through randomization, whilst the binding between the other two was swapped on the test trials, to be detected by the participant. The unchanged and randomized conditions were to be compared to study how far the relevance of this feature affected the detection of swaps between the other two features.

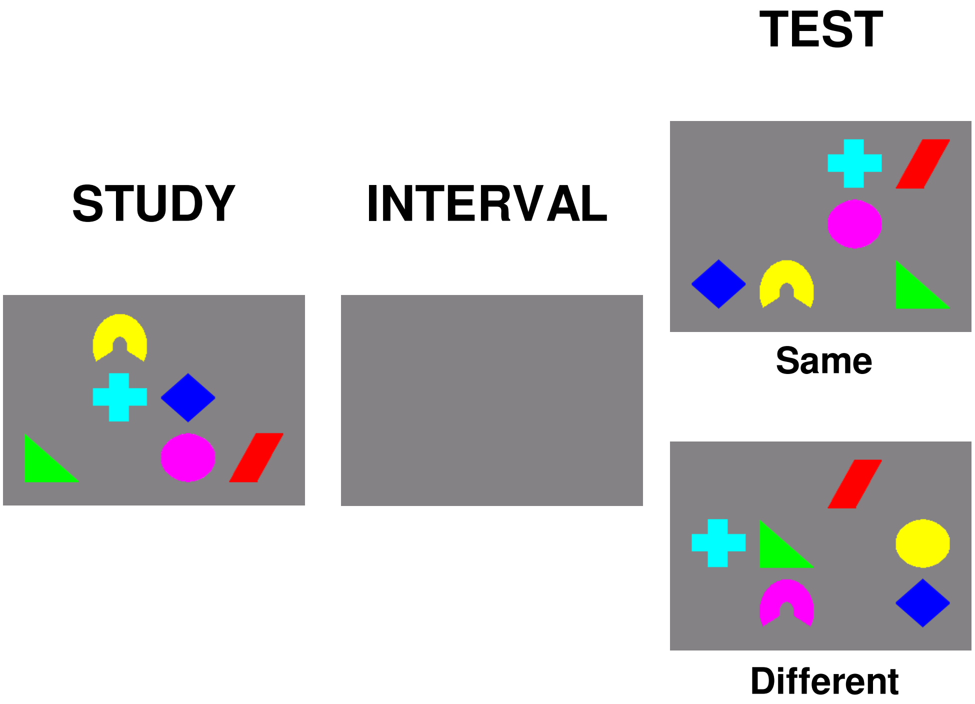
The operational problem was how to design a task that would 'break off' one of these elements to study the link or 'binding' between the other two. One solution could have been to hold this element constant. For example, presenting various shapes in various locations, and swapping any two, whilst keeping the colour of all the stimuli unchanged. Indeed this has been the procedure followed by many researchers in the field (e.g., Vogel et al., 2001; Wheeler & Treisman, 2002). However, it is questionable how far this manipulation prevents the inclusion of the irrelevant feature in the bound representation on each trial. If a feature is present constantly, it can still function as an informative cue. In fact, other features may be accessed through this feature. On the other hand, it may also block the effect of other features.

In the literature on conditioning, following Rescorla (1967), it is well established that the way to make a stimulus truly irrelevant and non-informative, is to randomize it. This idea was applied to the design of the present experiments by randomizing one feature between the study and test displays to render it non-informative, while testing memory for the combinations of the remaining two features of each object in the array. Using the swap detection task, location was randomized between the study and the test display with memory tested for the colour-shape combinations in the study display. Analogously, shape was randomized to study the link between location and colour, and colour was randomized to study the link between shape and location.

The task in the randomized condition used in the present research is a further variant of the feature swap detection task in the sense that in the test display, not only does the target change, but the distracters also change. The task becomes even more difficult, for participants have to decide whether there is a change in the binding of two features, when the third feature also changes. They have to ignore the changes in the one feature, and focus on finding the swap in the other two. This presumably involves a more demanding and central cognitive process in which the subject has to consider each of the stimuli in the test array, and compare whether the binding is the same as for the ones he holds in his memory. As such it is more like a test of recognition, the only difference being, that in this case, the correct response is recognising not what has been seen before, but what has not been seen before. Figure 3.1 shows the swap detection task as it appears to the participant in the randomized location condition.

Figure 3.1

An example of the swap detection task (randomized location condition)



ARTICULATORY SUPPRESSION

To get a relatively pure assessment of VWM, most researchers give the participants some verbal load whilst they perform a visual task (e.g., Allen et al., 2009; Zhang & Luck, 2008). Despite that Treisman and Zhang (2006) found that articulatory suppression has little differential effect on memory for shape and colour bindings at 100 and 900 ms, it was decided to use articulatory suppression in the present research. This was because even longer study-test intervals than Treisman and Zhang (2006) were being used. Further, the stimuli were nameable, being a combination of geometrical shapes in easily recognizable colours. Due to the relative ease of coding such stimuli in linguistic terms, it was argued that participants might try to remember those using verbal codes, particularly in the conditions with longer study-test intervals. To preclude such effects, articulatory suppression (saying ‘the’ repeatedly and rapidly) was used from fixation until after the response was given in all conditions. Studies show that even the repetition of a single item disrupts verbal coding of visual material, and more complex manipulations, such as increasing the load to several items, are not necessarily more effective (reviewed by Baddeley, 1986).

SIX STIMULI

The general consensus regarding the capacity of VWM is in the vicinity of 3-4 items (Cowan, 2005, 2009; Luck & Vogel, 1997; Vogel et al., 2001; Wheeler & Treisman, 2002; Zhang & Luck, 2008). Jiang et al. (2000) used a set size of eight, i.e., they presented eight stimuli with the response accuracy being about 74%. But they did not study memory for bindings. A perusal of Wheeler and Treisman, (2002) showed that, with a whole display that randomized location at test, and with set sizes varying from 2 to 6, they obtained 70% correct responses for the binding condition in one experiment, and 82% in another. It was decided to use six stimuli in the present research to avoid ceiling effects and make the experimental task difficult enough to ensure adequate variability in the performance of the participants, and yet to get performance above chance levels.

APPARATUS

On each trial, displays consisted of six stimuli created by randomly combining six shapes and six colours, placed within an imaginary 3×4 grid subtending 6.1° × 7.8° vertically and horizontally. Each stimulus subtended 1.6°×1.7° of visual angle. All stimuli were displayed on a grey background on a 43 cm (41 cm viewable) computer screen in a room lit by overhead lighting. Participants viewed these stimuli from an unconstrained distance of approximately 1 metre and could move their eyes freely during the task.

The experiments were designed using E Prime software (Psychology Software Tools, 2002). Responses were collected through a response box. Participants reported if there was any change from the initial to the test display by pressing the key to the extreme left for ‘same’ and the key to the extreme right for ‘different’. They used the index fingers of both hands, pressing ‘same’ with the left hand, and ‘different’ with the right hand. Buttons were not counterbalanced to avoid spatial conflict and because accuracy of response was the dependent variable anyway.

PROCEDURE

All participants were students of University of Edinburgh. They all reported normal colour vision and normal or corrected to normal visual acuity. Though informed consent was obtained from them, they were naïve to the experimental hypotheses. They came on two successive days at roughly the same time of the day for the two experimental sessions (except for Experiments 8, 9, 10 and 14 which were done in single sessions). First of all, they read through a detailed description of the study presented on the computer monitor. They were informed that they could pause any time between the trials simply by not pressing any key to move to the study display from the fixation screen. They were also told that change would occur on 50% trials. Participants were asked to aim for maximum possible accuracy, without any regard to speed of response.

Then they practised each experimental condition. There were a total of 40 practice trials in each session of Experiment 1 and 48 in all subsequent experiments. Participants could ask questions anytime, the experimenter being present throughout the study. Thereafter the actual trials commenced. Two small breaks were enforced in each experimental session, though the participants could take rest pauses at their own convenience as well. At the conclusion of each session, participants wrote a retrospective report describing any strategies/methods used to hold the relevant features together in their mind. They were fully debriefed at the end of the experiment. The variations from this general procedure are indicated as each experiment is detailed in the following chapters.

TRANSFORMATION OF SCORES AND STATISTICAL ANALYSES

Accuracy of response being the dependent variable, scores were transformed into d-primes for individual subjects. Hits were defined as a response of 'different' on the trials where a swap occurred. False alarms were defined as a response of 'different' when there was no change in the two displays. Following convention, hits of 1 and false alarms of 0 were converted using the standard method of subtracting 1/(2N) from a hit rate of 1 and adding 1/(2N) to a false alarm rate of 0, before d-prime and beta were calculated. However, these were rare occurrences.

Beta was also calculated and is reported in the appendices. In all experiments, there was a bias to respond 'Same' which varied in degree with the study-test intervals, rendering A' inaccurate as a measure of sensitivity. In all analyses in this thesis, d-prime is used, as it takes account of bias, and is a pure measure of sensitivity.

A new sample of participants was used in each of the experiments. The samples being drawn from a normally distributed population based on random independent sampling, Analysis of Variance was the statistical technique used for analysing the results. There were no gross violations of normality in the data for any of the experiments, except for outliers in a couple of experiments, which were *not* deleted. Where sphericity was violated as indicated by a significant Mauchly's test, F values with Greenhouse-Geisser correction applied to the degrees of freedom are reported, though in no case did this lead to a different conclusion than when sphericity was assumed. For all statistical tests, probabilities less than .001 are reported as .001. *Partial* η^2 is reported as a measure of effect size. It was chosen over other measures because the successive experiments in this thesis reflect changes to the basic paradigm by using additional variables. In such a scenario, *partial* η^2 is recommended as an easily understandable measure of comparisons of effect sizes across experiments (Cohen, 1973, Levine & Hullett, 2002). All relevant tables appear as Appendices A, B, C, D, and E, respectively for Chapters 4, 5, 6, 7, and 8.

To enable easy comparison across experiments, all graphs are drawn to the same scale on the y-axis, expressing d-primes from 0 to 4, even though in a few experiments the scores of the participants have a lower range. However, the results of serial position analyses in Chapter 8 are shown with the y-axis expressing d-prime from 0 to 2.5 to depict the serial position effects with greater clarity. The error bars in all graphs represent ±1 standard error of the respective means.

CHAPTER 4

EXPERIMENT 1

Among the three features defining the stimuli in the present work, location, colour and shape, it seemed logical to use location as a starting point, for it is ascribed a special status by many different researchers (Treisman & Gelade, 1980; Moore & Egeth, 1998; Wolfe, 1994; Zhang & Luck, 2009a). Not only is it held to be the basis of binding of other features (Kahneman et al., 1992; Treisman, 1996, 1998, 2006), but it is also processed in the dorsal stream, which allows faster and relatively more automatic processing as compared to the ventral stream processing other features (Ungerleider & Mishkin, 1982; Vecera & Palmer, 2006; Velichkovsky, 1982, 2007).

Location is such an overwhelming cue for encoding stimuli and their features, that it is invariably used if present (Jiang et al., 2000; Hollingworth, 2007; Mitroff & Alvarez, 2007; Richard, Luck, & Hollingworth, 2008; Van der Sigchel et al., 2007; Wyble et al., 2009). Even when the stimuli vanish, location aids retinotopic as well as spatiotopic representation of information in iconic memory (Breitmeyer et al., 1982; Feldman, 1985; McRae et al., 1987; Sligte et al., 2008).

In the domain of visual perception, the feature integration theory (Treisman & Gelade, 1980; Treisman & Sato, 1990) holds that, in contrast to other stimulus properties, location plays a key role in binding. According to the theory, while basic visual features are detected relatively automatically, participants cannot know which of these features go together unless attention is focused on particular locations. Treisman and Gelade (1980) noted that directing attention to a point in space precedes the identification of information at that location. This leads to the conclusion that focusing attention on a particular spatial location allows the features at that location to be bound together so that an item can be identified. Empirical research supports the idea that location is important in feature binding in perception (Fahle & Koch, 1995; Keele et al., 1988).

However, the significance of locations may prevail only in the initial identification of the stimulus or its features. Once established, the representations can become independent of location. There is clear evidence that when locations are not crucial for task performance, representations in VSTM do not necessarily include or rely on information regarding absolute locations. Indeed this is one fact that serves to distinguish VSTM from iconic memory. Phillips (1974) showed that change detection performance for displays of matrix patterns was enhanced when test displays were presented at the same retinal location as the sample display at short study-test intervals. However, the results also suggested that these representations in iconic memory are short lived, whereas performance over longer study-test intervals which relied on VSTM representations did not benefit from constancy in location between study and test.

Irwin (1991) investigated trans-saccadic integration using patterns of dots. He compared three experimental conditions. In the saccade condition, two patterns were presented in the same location, but were viewed in separate fixations, i.e., the participant was instructed to move his eyes between fixations. In the retinal + spatial condition, patterns were presented in the same location whilst the subject maintained fixation. In the no overlap condition, the patterns were presented in different locations with no retinal or spatial overlap, with the subject maintaining fixation at the location of the second pattern. The assumption was that the retinal + spatial condition would engage sensory memory, whereas the no overlap condition would rely on VSTM. He found that the pattern of performance in the saccade condition was similar to the no overlap condition, and thus concluded that trans-saccadic integration relied on conceptual, diffuse, capacity limited, short term memory store. Interestingly, he also noted an initial rise in performance in the no overlap condition in two experiments, and attributed it to the idea that it took a while to build a durable code in VSTM, i.e., consolidation of the first pattern took a while. This rise was also observed in the saccade condition, particularly when the second pattern was displaced relative to the first. He did not consider why such an increase was not found in the retinal + spatial condition, where it would have been further augmented by the patterns being presented at the same location. Irwin (1992) showed that the identities and not the positions of items in an array filled with letters of the alphabet were important for trans-saccadic memory, further substantiating that trans-saccadic memory or VSTM was object rather than location dependent.

Jiang et al. (2000) used a change detection task where the participants had to detect changes in colour, or in shape, or in location. They found that the global spatial configuration was important for all these detections, and thus concluded that VSTM stores relational information. They also proposed that remembering item locations in relation to each other plays an integral role in the memory for other features such as colour, implying that location was in some sense more important than other features. Disrupting the spatial layout interfered with retrieval of location as well as colour and shape, though disruption of the pattern of colours had no effect on memory for locations. The complexity of the global configuration apparently has no effect on performance. Alvarez and Oliva (2007) derived an index of spatial regularity and confirmed that change detection was easier when the change altered spatial regularity, than when it did not, though the overall level of spatial regularity in any one display had no effect on probability of change detection. Note however, that both these studies using change detection, also addressed changes in single features, and did not study changes in bindings.

Yet, using real objects as stimuli in a change detection task with 900 ms between the study and the probe display, Hollingworth (2007) reported better performance when the object remained in the exact same position. However, if all the other objects changed their relative spatial relationships, this same position advantage for the target was lost, indicating that the map of the visual space as a whole is a critical factor in the memory for objects even at 900 ms. The importance of location for bindings in VSTM has been established not only for objects placed in a two-dimensional single plane, but also when they are placed in 3-D surfaces. A greater number of objects could be held in VSTM when they were placed in two different

3D surfaces (either vertical or horizontal) than in a single plane. This advantage was evident, however, only when participants had to bind which colour appeared where. When the colour-location binding was not required, and participants were to remember only colours, no benefit accrued from the extra spatial dimension. In other words, the extra dimension, being germane to locations, was important for the response only when locations were a relevant feature in the memory of bindings (Xu & Nakayama, 2007).

This circuitous evidence allows the inference that VWM is not influenced by absolute location of items except when location is bound with other features as in real objects or is relevant to task performance. Nonetheless, applying feature integration theory to memory, Treisman (2006) held that location has an important role in the binding process because it provides the basic framework to which other features are attached. As attention is directed to each spot in visual space, selecting one location after another, other features are bound to a master map or template of locations by the glue of attention. In this sense, she is proposing that location is important even in memory whether or not it is task relevant. She argues further that both individual features and bound objects are held in the VSTM.

To assess whether or not individual features were held in memory independently of object files, Treisman and Zhang (2006) examined the impact of changing locations between the presentation and the test display on memory for bindings of shape and colour of three objects. In effect, this is one of the few studies directly addressing the ‘special role’ of location in memory for feature bindings, Changing location disrupted memory for bindings with a 100 ms study-test interval between stimulus offset and the test display. The disruptive effect was much smaller when the study-test interval was 900 ms, and there was no disruptive effect of changing locations with study-test intervals of three or six seconds. While Treisman and Zhang (2006) infer from this that individual features are held in memory separately from bound objects, the evidence can also be taken to suggest that bindings of other stimulus features (e.g. colour and shape) might be stored in VSTM independently of location if they are required for the task, even if location is crucial for the initial detection of those other features and their encoding. That is, location may be important for initially generating object representations but may not be so crucial once those representations are transferred to VSTM.

One often can recognise or recall objects, without remembering where they were initially seen. Exactly when location loses the paramount place it has in perception is the focus of this study. In terms of the top-down vs. bottom-up debate, the experiment asks whether it is possible to selectively bind the relevant features while ignoring the irrelevant features. Whether locations are inevitably bound in the stimulus representations or if it is possible to selectively bind colour and shape and ignore information about locations is the focus of this initial experiment designed to assess the role of relevance of locations in feature binding at different study-test intervals.

EXPERIMENT 1

Experiment 1 was designed and conducted in early 2006 without the knowledge of the experiments reported by Treisman and Zhang (2006). To ensure that the experiment covered the whole period during which VWM might affect the stimuli, a broad range of study-test intervals – 0, 200, 1500, 2800 and 4100 ms were used.

On the basis of earlier studies by Phillips (1974) and Irwin (1991), it was predicted that location would be important at the shorter study-test intervals, but would cease to be important at the longer study-test intervals. Thus, it was expected that randomizing locations from study to test would disrupt performance to a great extent at 0 and 200 ms when performance would be primarily driven by the contents of iconic memory, but not so much at 1500, 2800, and 4100 ms, when the iconic representation would have decayed. At these longer intervals, performance would be driven by integrated object representations in VSTM comprising colour and shape. In the unchanged locations condition, location should benefit performance at the shorter study-test intervals when the locations in the test array match the locations in iconic memory. In the randomized locations condition, there being a mismatch between the study and test displays, performance would be disrupted at the shorter study-test intervals while the iconic memory for the study display still lingers. At the longer study intervals, iconic memory would have faded, and locations being task irrelevant, would not be part of the representations in VSTM. A match or mismatch between the study and test arrays would have no effect at the longer study-test intervals in either the unchanged or randomized locations condition. Thus, an interaction showing a large discrepancy between conditions at short intervals but a convergence of performance levels at longer intervals would occur. It was a special interest to assess exactly when the interaction happens, for this would also dictate the study-test intervals to be used in future experiments. Planned comparisons using paired samples directional t ratio would be used to test differences between performance under unchanged and randomized locations conditions at each study-test interval.

Thus, Experiment 1 tests the impact of unchanged and randomized locations at study-test intervals of 0, 200, 1500, 2800, and 4100 ms on the accuracy of response. The experiment uses a change-detection task in which participants judged whether two temporally separated study and test displays of six items were the same or different in their colour-shape bindings. Critically, for half of the trials, the location of items in the test display was randomized as compared to the study display to make location non-informative and irrelevant for the performance of the participants. On the other half of the trials, locations of objects remained unchanged from study to test. To assess memory for bindings, for the trials on which a binding change occurred, the colour-shape pairings of any two items were swapped.

The task for the participants in the experiment was to detect a swap either in shape or in colour. Given that the stimuli were defined by three features, in the unchanged condition, when either of the two dimensions swapped, there was no change in the relationship of the second dimension with the third. So a colour swap meant that two colours changed shapes as well as locations, but the shape-location relationship did not change. Analogously, a shape swap entailed two shapes swapping colours as well as locations, but no change in colour-location relationship. In the randomized condition, when a change was made in any of the two target features, because the irrelevant feature randomly changed as well, the third dimension automatically changed. This implied a change in all three possible relationships – colour-shape, colour-location, and shape-location. Thus the appearance of the test display was different in the unchanged and randomized locations condition as illustrated by Figure 4.1. It was also possible that the type of swap would differentially affect performance in the unchanged and randomized locations condition. This despite the fact that the participant did not know beforehand whether shapes would swap or colour would swap. Additional analyses were planned, separately in the unchanged and randomized conditions, to explore if the type of swap affected the performance of the participants and if the differential processing of the features involved in the swap might affect performance.

Participants

Ten postgraduates (5 men and 5 women) in the age range 23-35 years voluntarily participated in the experiment.

Stimuli

The stimuli were created by randomly combining six shapes (circle, plus, right triangle, horseshoe, diamond, parallelogram) and six colours (yellow, cyan, magenta, blue, red, green) without replacement, and were randomly placed within an imaginary 3×4 grid.

Design and Procedure

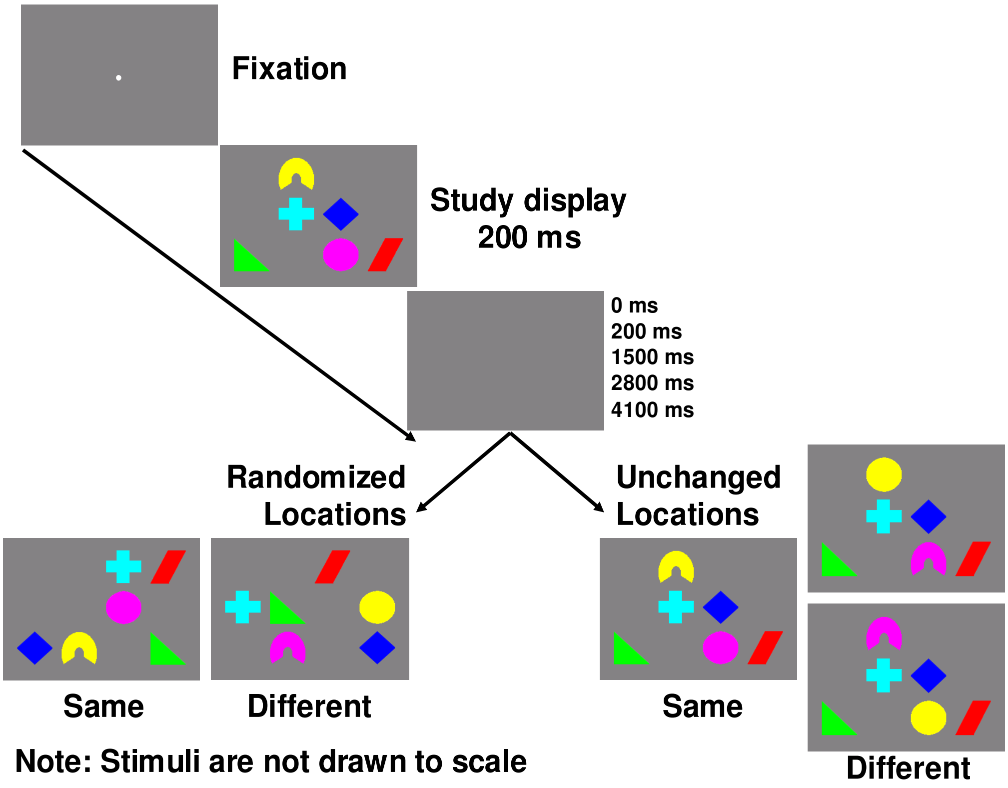
The experiment was designed as a 2×5 factorial experiment with repeated measures on both factors. The first independent variable was location manipulated at two levels: unchanged locations vs. randomized locations. In each trial, stimuli appeared in any six locations within an imaginary 3×4 grid. In the unchanged locations condition, they remained in the same locations in the test display. In the randomized locations condition, any six out of twelve locations were again randomly selected to present the stimuli in the test display, and thus locations were randomized from study to test. The second independent variable was the study-test interval between the initial and test display. The study-test intervals of 0, 200, 1500, 2800, and 4100 ms were chosen as the five levels of this factor. These different study-test intervals were chosen with the assumption that whereas perceptual factors would dominate at the shorter study-test intervals, the longer study-test intervals would yield a relatively pure measure of memory. The test display itself requires visual scanning and has a large element of visual search. This was necessitated in order to investigate the impact of one of the main experimental manipulations, namely, randomizing locations between study and test to render it irrelevant as a condition of the first independent variable.

Each trial commenced with a ‘fixation’ display of a small pinpoint of light at centre-screen. When the participant was ready, any key on the response box was pressed to see the study display. It showed six stimuli presented simultaneously in randomly chosen locations for 200 ms. After a blank interval, the test display was shown, which was different from the initial display on 50% of the trials. On ‘different’ trials, the combination of colour and shape was swapped randomly for any two items. When the location of the stimuli was unchanged from the initial to the test display, on half of the ‘different’ trials, two stimuli swapped colour at their locations, whereas on the other half, two stimuli swapped shapes at their locations. When the location of the stimuli was randomized from the initial to the test display, swapping one feature implied swapping the other too.

With three blocks for each study-test interval in each location condition, 30 blocks of 20 trials each were counterbalanced within and across participants to preclude immediate sequential effects. Each participant completed 600 trials in the whole experiment. A brief rest pause was given after every five blocks. Participants were tested on two consecutive days at the same time of the day. On the first day, half of them were tested with randomized locations, and the other half were tested with unchanged locations, with the remaining condition completed on the successive day at roughly the same time. Before each of the two experimental sessions, participants practised eight trials of each block type, starting from the longest study-test interval, and working gradually through all the study-test intervals to the shortest one of 0 ms. Figure 4.1 elucidates the design and procedure.

Figure 4.1

Sequence of events in Experiment 1



Note: Stimuli are not drawn to scale

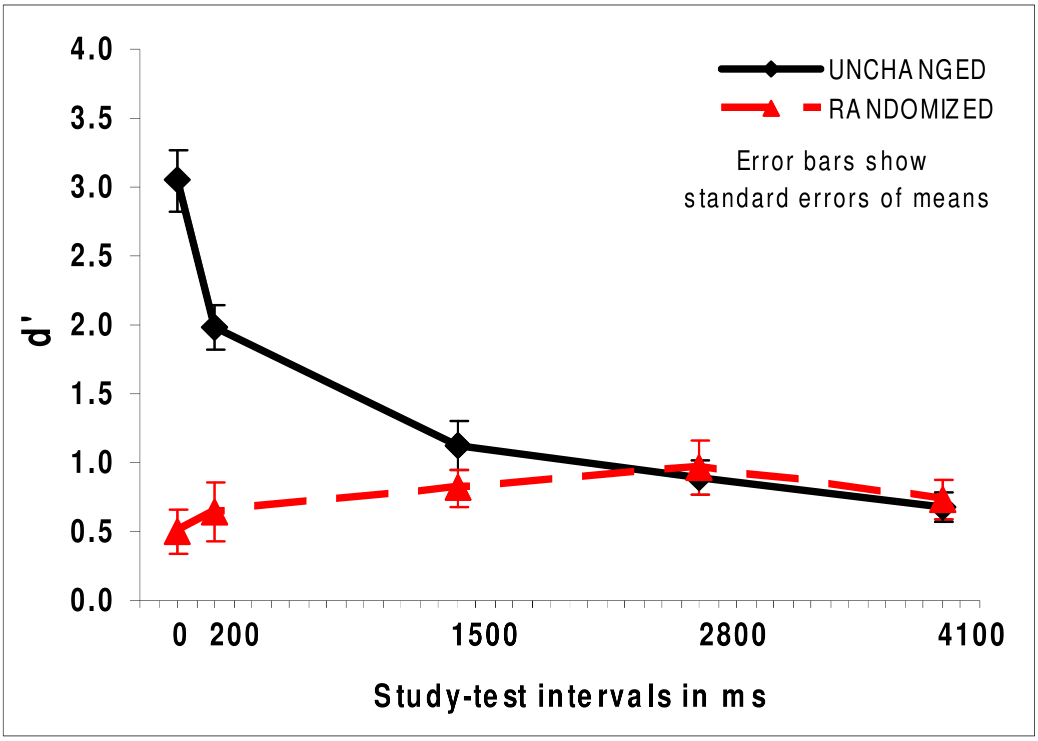
Results

Mean change detection performance calculated from d-primes is shown in Figure 4.2. Repeated measures ANOVA revealed a reliable main effect of unchanged/randomized locations, $F(1,9)=86.481$, $MSE=.193$, $p<.001$, *partial* $\eta^2=.906$, in that, overall, swap detection was reduced when locations of stimuli were randomized between study and test than when locations did not change. The main effect of study-test interval was also reliable, $F(4,36)=19.922$, $MSE=.175$, $p<.001$, *partial* $\eta^2=.689$, indicating that swap detection varied across study-test intervals.

These factors interacted, $F(4,36)=34.466$, $MSE=.184$, $p<.001$, *partial* $\eta^2=.793$. Separate single degree of freedom polynomial tests within each condition were conducted to further investigate the nature of the interaction. In the unchanged locations condition, performance across study-test intervals was characterized by negative-slope linear $F(1,9)=125.461$, $MSE=.271$, $p<.001$, *partial* $\eta^2=.933$, and quadratic, $F(1,9)=16.819$, $MSE=.231$, $p<.003$, *partial* $\eta^2=.651$, trends. In contrast, for randomized locations, performance was characterized by a positive-slope quadratic trend, $F(1,9)=5.819$, $MSE=.073$, $p<.039$, *partial* $\eta^2=.393$.

Figure 4.2

Mean performance for unchanged and randomized locations for each study-test interval in Experiment 1



Planned comparisons using paired samples directional t tests with Bonferroni adjustment showed that differences between the means for the unchanged and the randomized condition were reliable at 0 ms, $t(9)=16.222$, $p<.001$, and 200 ms, *t*(9)=5.004, *p*<.001, but not thereafter. Thus randomizing locations was disruptive of performance only at the shorter study-test intervals.

The bias in all conditions was to respond 'same' as noted in the section on statistical analyses in Chapter 3. It is interesting to note that the participants have a tendency to respond 'same' even in the randomised location condition at the very short study-test intervals of 0 and 200 ms, despite that the phenomenal experience in these conditions is that 'everything is changed'. Indeed, one might interpret the bias to respond 'same' in these conditions as a testimony to the motivation of the participants to respond 'different' if and only if they actually perceive a change in the binding between colour and shape. In other words, they respond 'different' only when they are certain.

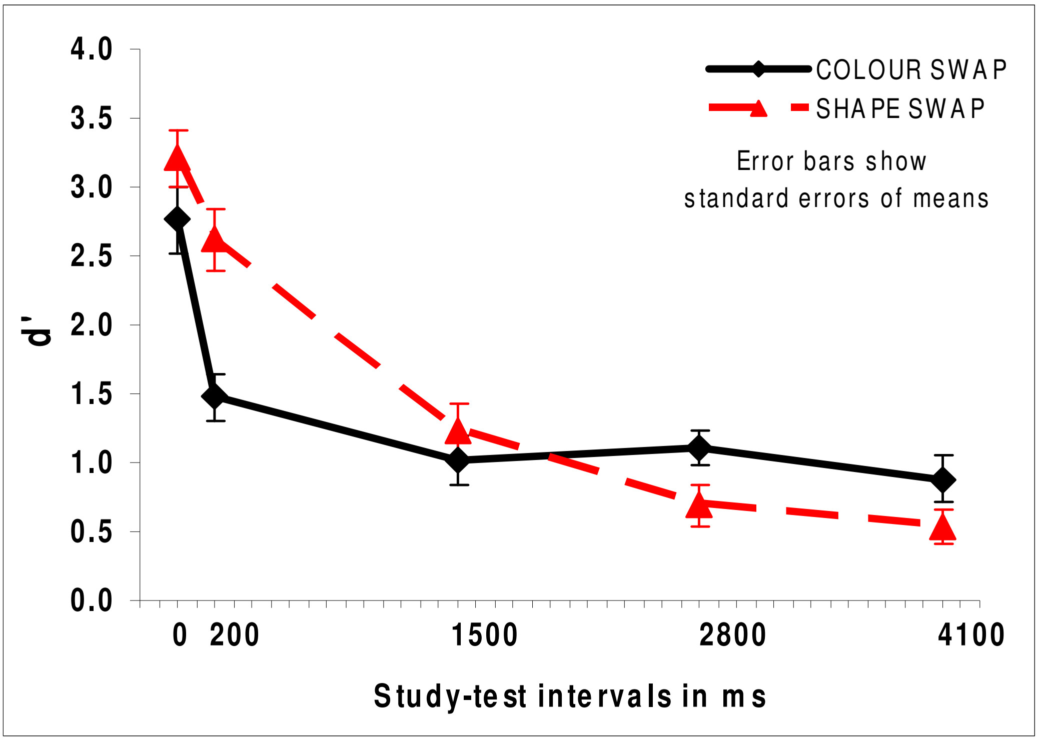
Comparing swaps

Additional analyses were done to test if the type of swap had any effect on the performance of the participants. Analyses for swaps in the randomized locations condition did not reveal any significant effects. However, in the unchanged locations condition, there was a significant main effect of swaps, *F*(1,9)=4.947, *MSE*=0.224, *p*<.053, *partial* η^2=.355. Overall, a shape swap was detected more often than a colour swap. The swap × study-test interval interaction was also significant, *F*(4,36)=16.552, *MSE*=0.123, *p*<.001, *partial* η^2=.648. Planned comparisons using paired samples t tests with Bonferroni adjustment showed that whereas a shape swap was detected more often than a colour swap at 200 ms, *t*(9)=6.082, *p*<.001, a colour swap was detected more often than a shape swap at 2800 ms, *t*(9)=3.798, *p*<.004.

Separate single degree of freedom polynomial tests for each kind of swap were also conducted to investigate the nature of the interaction. For colour swaps, linear *F*(1,9)=27.405, *MSE*=.623, *p*<.001, *partial* η^2=.753, and quadratic, *F*(1,9)=19.058, *MSE*=.262, *p*<.002, *partial* η^2=.679, trends were significant. For shape swaps, linear *F*(1,9)=312.361, *MSE*=0.170, *p*<.001, *partial* η^2=.972, quadratic, *F*(1,9)=12.450, *MSE*=0.170, *p*<.006, *partial* η^2=.580, and cubic, *F*(1,9)=7.719, *MSE*=0.181, *p*<.021, *partial* η^2=.462, trends were significant. Figure 4.3 depicts this result.

Figure 4.3

Mean performance for shape swaps and colour swaps with unchanged locations for each study-test interval in Experiment 1



Discussion

As expected, results show that location is a significant factor in binding only at shorter study-test intervals, the difference ceasing to be significant at longer study-test intervals. The differential performance obtained at short study-test intervals (0 and 200 ms) offers support for the predictions of the feature integration theory and the broader literature on iconic memory suggesting that location has an important role in the initial processing of visual displays. At longer study-test intervals, even if location information is made uninformative by randomization, it makes no difference to the retrieval of bindings, because the performance levels are indistinguishable from the unchanged locations condition.

In the main result depicted in Figure 4.2, three features of the data are striking. The very high levels of performance in the unchanged locations condition at 0 ms suggest that location was a highly effective cue in binding. But, this beneficial effect disappears for study-test intervals of 1500 ms or more, with performance for randomized locations statistically identical to performance for unchanged locations. This suggests that changing locations does not have an impact on bindings of task-relevant features held in VWM. From these results, it seems that binding between location, shape, and colour takes place during stimulus presentation and the period shortly thereafter comprising iconic memory. As the study-test interval increases, location becomes irrelevant as a cue for maintaining bindings in memory, even in the unchanged locations condition when it might potentially be useful. Second, extending the study-test interval beyond 1500 ms does not appear to result in any reliable change in performance, suggesting that the bindings available at 1500 ms can be maintained at the same level for more than four seconds following presentation regardless of whether or not location changes. Third, performance in the randomized locations condition generally improves with increased study-test intervals, suggesting that there may be a process of removal or inhibition of the task-irrelevant feature as bindings comprising the relevant features, colour and shape, are consolidated in VWM.

One possible account, considering the findings above collectively, is that up to around 1000 ms, information is available from a rapidly decaying iconic trace, but there is progressive formation of a representation in VSTM of the task-relevant feature bindings. The decaying iconic trace would contain both task-relevant features and the task-irrelevant feature of location for items in the study array. So, based on this decaying representation, location acts as an effective cue for the unchanged location condition, but is disruptive in the randomized location condition. During that same period of around 1000ms, only the task-relevant features are transferred into a representation in VSTM, and so memory performance would rely progressively less on the decaying icon and progressively more on a more stable representation of the task-relevant features in VSTM. The formation of the more stable representation might be thought of as a form of 'consolidation' in VSTM (e.g., Brockmole et al., 2003; Jiang et al., 2000). Since location is not task relevant, it would not be included in this more stable representation, and so with increasing study-test delays, location becomes progressively less effective as a memory cue in the unchanged condition (contributing to progressively poorer performance), and progressively less disruptive in the randomized condition (resulting in progressively better performance). This idea that performance is supported concurrently by two changing, and possibly conflicting memory codes over the first 1000 ms - a decaying iconic trace and progressive consolidation in VSTM - is supported by the observation that performance in the two conditions converges as the study-test interval is increased, and at 1500 ms performance is no different for the randomized and the unchanged conditions, when on this account, performance is supported solely by VSTM.

The difference between unchanged and randomized location conditions in the initial stages might also reflect the operation of top-down factors through two different kinds of attention. Participants may rely on spatial attention in the unchanged location condition, whilst using an object or feature based attention in the randomized location condition. Since spatial attention can operate only in the presence of spatial information present at the time of perception and shortly thereafter in iconic memory, performance in the unchanged location condition is higher at the short study-test intervals and gradually decreases thereafter. In the randomized location condition, participants, unable to rely on spatial attention, use an object based or feature based strategy. They select only the relevant information regarding the objects presented to them, and suppress all the bits of information that they know are task irrelevant. This process of selective consolidation and active inhibition takes time and therefore, performance shows a gradual increase in this condition.

The results are remarkably similar to the results of Treisman and Zhang (2006) who also found that changing locations between study and test had a disruptive effect on performance at a study-test interval of 100 ms, but this disruptive effect was greatly reduced at a delay of 900 ms, and disappeared at longer delays of three and six seconds. Nevertheless, it is important to realise that the motivation for the study by Treisman and Zhang (2006) was to assess whether object files are the only memory traces available, or are separate features stored in VSTM as well. The rationale for the experimental manipulation whereby bindings were changed in the probe at various intervals was that this would disrupt memory for features as well, if object files were the only memory traces. Since memory was not disrupted at longer study-test intervals it allowed the conclusion that VSTM stored separate features as well as object files.

The question for the present experiment was that given an attention demanding task, is binding instantaneous and automatic for all features, or whether it is possible to ignore or delete irrelevant features and selectively bind only the relevant features over a course of time in VWM. The similarity of the experimental manipulation to Treisman and Zhang (2006) and the consequent data obtained should not detract from the fact that Treisman and Zhang (2006) are silent on the matter of task-relevance of features, whereas it is the central issue in the present experiment. Going beyond their insistence that features continue to exist in an attenuated form in separate feature maps in VWM, the present proposal is that once features are categorised as relevant and irrelevant, they are differentially processed thereafter. There is no going back to previous stages. Further, Treisman and Zhang (2006) assume location to be a crucial feature for binding, but the argument presented here is that the times for processing different features reflect differential processing in the underlying neural system for each feature, but the way VWM deals with the features is the same; they are selected for further processing if they are relevant and inhibited if they are not relevant.

The results of additional analyses which showed differences in performance between colour swaps and shape swaps in the unchanged locations condition substantiates the notion that differences in the processing of the three features may be reflected in the performance of the participants. At the shorter study-test intervals, the participants may be remembering colour-location and shape-location bindings, rather than colour shape bindings. This implies that colour-shape bindings may be encoded via the attachment of separate feature maps to the underlying spatial map which presumably exists only until iconic memory decays. Alternatively, these differences may simply reflect the asynchronous processing rates of different features by the visual system. These different ideas augment the impetus to study whether a similar pattern of results would be obtained when either colours or shapes are made irrelevant to the task, which is the focus of the experiments reported in the next chapter.

There is no significant difference in performance beyond the study-test interval of 1500 ms. Also, it is not clear how performance is characterized at intermediate study-test intervals between 200 and 1500 ms; for example, whether the trends are linear, suggesting a gradual process of binding, or whether there is a step change that would indicate a discrete point when bindings of task-relevant features are formed. This is important, given the large variability, in the estimates for consolidation in VWM. With these factors in mind, it was decided to use finer gradations between the different study-test intervals ranging from 0 to 2500 ms in the experiments comparing the effects of randomising the three different features, reported in the next chapter. This should make it possible to identify when the disruptive effect of randomizing a feature disappears, and whether or not the effect is a gradual change.

CHAPTER 5

EXPERIMENTS 2, 3, AND 4

The guiding enquiry for the experiments reported in this and the next chapter is whether all features are inevitably bound together instantaneously or in the embryonic stages of the binding process; or is it possible to ignore a feature from the start if it is irrelevant, and if not, when does this become possible. Further, across three experiments, the effect of assigning different features as task irrelevant was examined to ascertain whether differential processing of features is present beyond their initial perception. In Experiment 2, location was task irrelevant, with shape-colour binding being tested. In Experiment 3, shape was task-irrelevant with colour-location binding being tested, and in Experiment 4, colour was task-irrelevant with shape-location binding being tested.

If performance is dictated only by top-down task set, then the participants would process the relevant dimensions and simply ignore the irrelevant dimension. There would be no difference in performance in the randomized and unchanged conditions because in each case the test display would need to be matched with the representation comprising only relevant features. However, if bottom-up influences are important and all features are processed irrespective of their relevance to the task, then performance in the randomized condition would be lower than performance in the unchanged condition, because of the greater mismatch between the mental representation and the test display in the randomized condition.

Previous empirical evidence and Experiment 1 suggest the third possibility that top-down processes gradually take over and win against the bottom-up, fast feed forward processing of all features. This would show up as an interaction such that the initial difference between unchanged and randomized conditions would vanish with the passage of time. Thus in all three experiments, randomization of a feature may result in lower performance as compared to the unchanged condition. The question of theoretical importance here is whether this disruption is maintained when study-test intervals are sufficiently long to have allowed the consolidation of stimulus representations into VSTM. If the disruption continues with long study-test intervals then it suggests that features, even if task irrelevant, remain in the representations and continue to affect the performance of the participants. If the disruption is no longer present at longer intervals, then it suggests that, over time, task-irrelevant features can be ignored, and the remnants would be the bindings between relevant features required for the task. This would be manifest as an interaction in the results of the experiment.

Such an interaction is expected not only because of the literature reviewed regarding locations in the previous chapter, and because the results of Experiment 1 may be generalized to other features, but also on the basis of theoretical notions regarding task relevance being the most important factor in top-down control of processing. Hommel (2004) proposes that task relevance of features is more important than their salience in the binding that takes place in event files, and asserts that it influences bindings in the incipient stages itself. The biased competition model (Duncan, 2006) holds that competition between objects is biased by task relevance more than anything else. The dimension weighting account (Muller et al., 2009; Muller & Krummenacher, 2006a, 2006b) which is essentially a feature based account of processing, acknowledges that weights assigned to different features can be modulated by expectancies set up through factors such as instructions, practice, past experience etc. Though the perceptual system initially processes all features, the selection of features for further processing is presumably based on task relevance.

It is also of interest to study if the interaction effect will be obtained for different features. When the experiments require different sets of features to be bound but the same pattern is obtained, it would indicate that top-down factors operate in a similar way across features. It is expected that the initial disruption in performance will differ in the three experiments to the extent that the bottom-up stimulus factors dictate the performance of the participants. Many studies have shown that features are processed differentially during perception (Aymoz & Viviani, 2004; Moutoussis

& Zeki, 1997; Nishida & Johnston, 2002; Viviani & Aymoz, 2001, Zeki et al., 1991). The experiments reported here explore the extent to which these differences in the perceptual phase of the binding process persist in memory for bindings. Some researchers contend that features are encoded in separate channels (Magnussen, 2000; Magnussen & Greenlee, 1997; Magnussen et al., 1996) or maps (Treisman, 2006) even in VWM. Still others have found evidence for memory performance reflecting processing differences in perception (Kent & Lamberts, 2006; Lamberts & Kent, 2008). Yet evidence from Lamberts and Kent (2008) also shows that when the features to be remembered are bound within a single object (as compared to appearing in two different objects), then no differences in the recognition of different features are shown. In fact, the differences between features emerged only when the participants had to remember six features in two different objects. Though they interpreted this as being due to memory load exceeding capacity, in view of evidence suggesting that capacity for remembering features within an object is virtually unrestricted (Luck & Vogel, 1997; Vogel et al., 2001), it is more likely that their results showed differences due to the occurrence of features in the same vs. two different objects.

Mitroff and Alvarez (2007) found that contiguity in space and time rather than surface features aids the persistence of objects, even when the object disappears for as long as 3 seconds. Nevertheless, Mitroff, Arita, and Fleck (2009) also report that objects are constrained by the boundaries of a closed contour, all parts and properties being contained within the object, and by the context in which they occur, and this is a significant factor in object persistence. Bartels and Zeki (2006) found that binding of features imposes a different schedule of processing, and in fact there is a reversal, in so far as the binding of colours takes more time than binding of stimuli that move and hence change location. This is in contrast to processing of individual features where movement is perceived much earlier than colours. They propose that whereas perceptual delays in feature processing reflect neuronal processing delays, the time required for binding reflects the velocity of signal conduction in distinct processing systems, substantiating the view that binding implies interactions among various areas of the brain. They conclude that binding is different from, and subsequent to, stimulus processing though it is an attribute-dependent process.

All this evidence suggests that binding of features within an object may lead to processing that is different from the processing of features otherwise (e.g., in the incipient stages of object formation, or when the object is not present, or when ‘unbinding’ is required). The experiments reported in this thesis do not compare processing of single features with processing of bindings. Rather, the differential processing of three features, which together define an object is the focus of study. In so far as features are processed in parallel independent channels, differences in performance across features are expected, reflecting bottom-up processing. If the features interact and accrue costs and benefits from being aspects of a single object, then performance should be exactly the same across the three experiments. If there is an interaction over time, it would suggest that features lose their individual identities only gradually over time as the top-down processes take over, maintaining only the relevant features in memory. Except that different features are randomized in each experiment, the experiments were exactly the same.

Assuming location to be a property of the stimulus, just like shape and colour, and to make it possible to compare locations with colours and shapes, Experiments 2, 3, and 4 were designed to be identical in procedural details, though this meant that Experiment 2 virtually replicates Experiment 1. Nonetheless, these experiments differed from Experiment 1 in that the study-test intervals used were restricted to 0-2500 ms, with binding performance being assessed at equal intervals of 500 ms. This ensured a more precise focus on the time course of the convergence of performance found in Experiment 1 and allowed an appraisal of whether or not the effects observed show a gradual or step change.

EXPERIMENT 2

As in Experiment 1, the detection of swaps between bindings of colour and shape was assessed when locations were unchanged from study to test or were rendered irrelevant through randomization. The study-test intervals were 0, 500, 1000, 1500, 2000, and 2500 ms. On the basis of the previous literature surveyed in Chapter 4 and the results of Experiment 1, it was expected that randomizing locations between study and test would be more disruptive of memory for shape-colour bindings at the shorter study-test intervals than at longer intervals. Analogous to Experiment 1, additional analyses were planned to study if the type of swap affected the performance of the participants and if the differential processing of the features shown in Experiment 1 might be manifest in performance.

Participants

Twelve students (3 men and 9 women) in the age range 18-25 years participated in the experiment and were given an honorarium of £10.00.

Stimuli

The stimuli, identical to Experiment 1, were random combinations of six colours and six shapes, placed at random locations in an invisible 3×4 square grid.

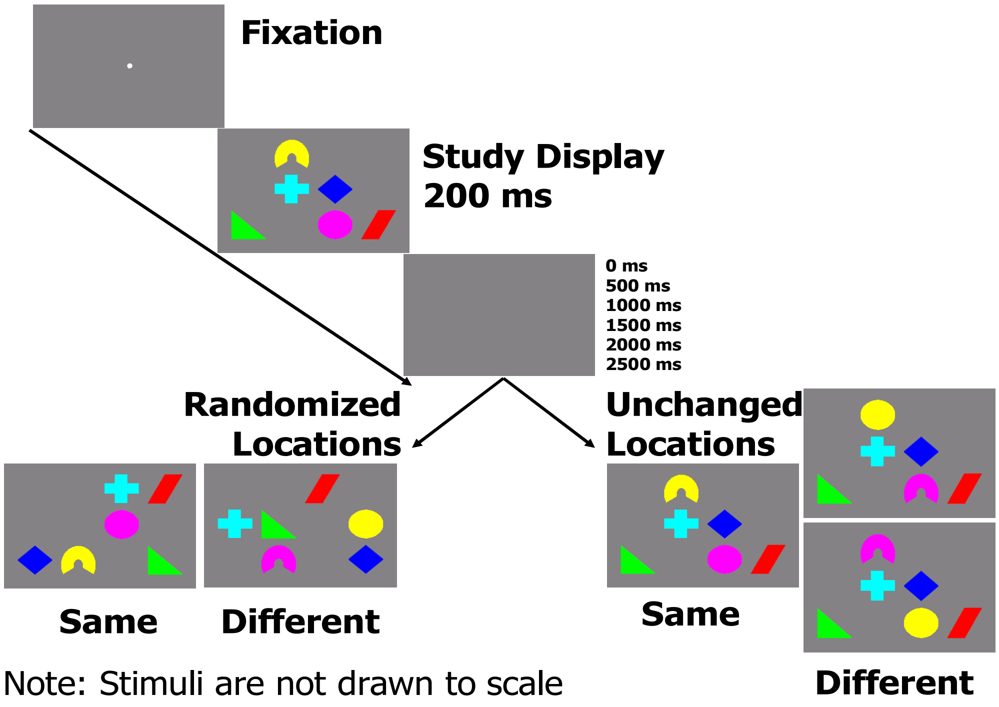
Design and Procedure

The experiment was designed as a 2×6 factorial experiment with repeated measures on both factors. The first independent variable was location manipulated at two levels: unchanged locations vs. randomized locations. The second independent variable was the study-test interval between the initial and test display. The study-test intervals of 0, 500, 1000, 1500, 2000, and 2500 ms were chosen as the six levels of this factor. With three blocks for each study-test interval in each location condition, 36 blocks of 20 trials each were counterbalanced within and across participants, 720 trials in all for each participant to complete the experiment. A brief rest pause was given after every six blocks.

Each trial commenced with a ‘fixation’ display of a small pinpoint of light at centre-screen. When the participant was ready, any key on the response box was pressed to see the study display. It showed six stimuli presented simultaneously in randomly chosen locations for 200 ms. After a blank interval, the test display was shown, which was different from the initial display on 50% of the trials. On 'different' trials, the combination of colour and shape was swapped randomly for any two items. When the location of the stimuli was the same from the initial to the test display, on half of the 'different' trials, two stimuli swapped colour at their locations, whereas on the other half, two stimuli swapped shapes at their locations. When the location of the stimuli was randomized from the initial to the test display, swapping one feature implied swapping the other too. Figure 5.1 illustrates the procedure.

Figure 5.1

Sequence of events in Experiment 2



Note: Stimuli are not drawn to scale

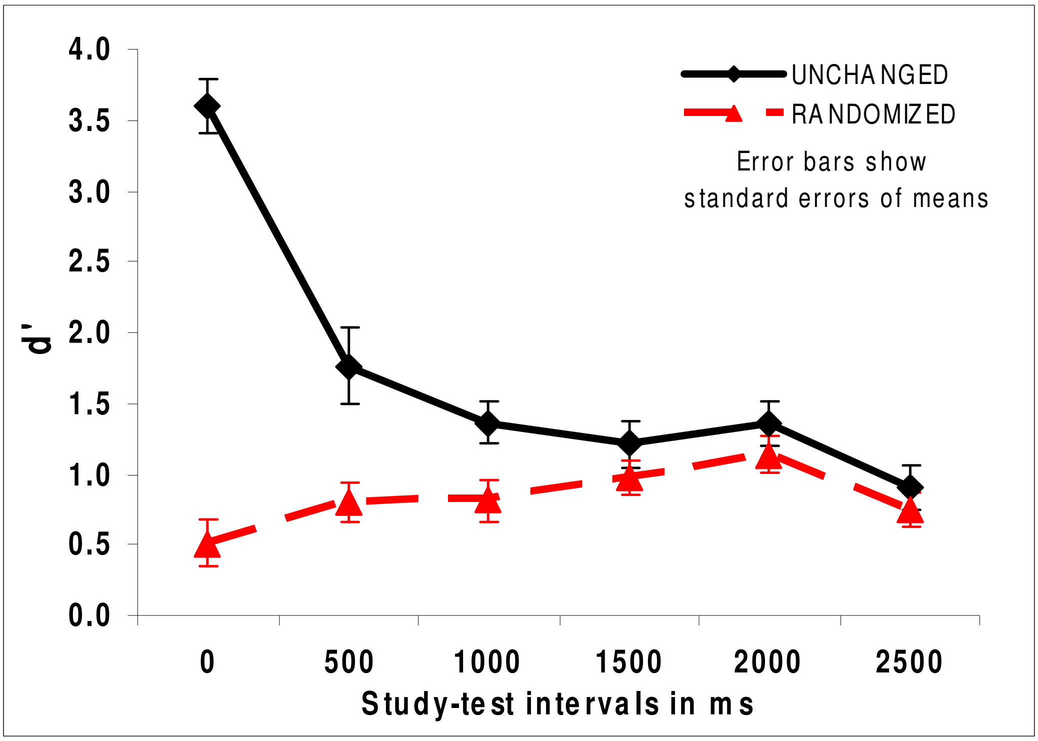
Participants were tested on two consecutive days at the same time of the day, half of them being tested with location changing randomly from initial to test display on the first day, and the other half being tested with unchanged locations on the first day. In each session, they practised 8 trials of each block type, starting from the longest study-test interval, and working gradually through all the study-test intervals to the shortest one of 0 ms.

Results

Mean change detection performance calculated from d-primes across study-test intervals and for the unchanged location/randomized locations conditions is shown in Figure 5.2.

Figure 5.2

Mean performance for unchanged and randomized locations for each study-test interval in Experiment 2



A reliable main effect of locations condition was observed, *F*(1,11)=44.958, *MSE*=0.606, *p*<.001, *partial* η^2=.803, in that, overall, memory for bindings was reduced when locations of stimuli were randomized between study and test. The main effect of study-test interval was also reliable, *F*(5,55)=27.903, *MSE*=0.151, *p*<.001, *partial* η^2=.717, indicating that memory for bindings varied across study-test intervals. As with Experiment 1, these factors interacted, *F*(5,55)=33.517, *MSE*=0.228, *p*<.001, *partial* η^2=.753. Planned comparisons using paired samples directional t tests with Bonferroni adjustment showed that the differences between the means for the unchanged and the randomized condition was significant at 0 ms, *t*(11)=12.784, *p*<.001, 500 ms, *t*(11)=3.419, *p*<.003, and 1000 ms, *t*(11)=2.823, *p*<.008.

Separate single degree of freedom polynomial tests within each condition were conducted to investigate the nature of the interaction. In the unchanged locations condition, performance across study-test intervals was characterized by negative-slope linear *F*(1,11)=131.030, *MSE*=.288, *p*<.001, *partial* η^2=.923, quadratic, *F*(1,11)=53.584, *MSE*=.220, *p*<.001, *partial* η^2=.830, and cubic trends, *F*(1,11)=53.422, *MSE*=.126, *p*<.001, *partial* η^2=.829. In contrast, for the randomized locations, performance was characterized by positive-slope quadratic trend, *F*(1,11)=7.114, *MSE*=.156, *p*<.022, *partial* η^2=.393. One slope being negative, and the other being positive, performance converged between the two conditions.

Thus, Experiment 2 generally replicated Experiment 1 in showing that randomizing location between study and test was highly disruptive of memory for colour-shape bindings, but this disruptive effect gradually disappeared.

Comparing swaps

On the lines of Experiment 1, additional analyses were done to test if the type of swap had any effect on the participants' performance. Neither the main effect for swaps, nor the interaction between swaps and study-test intervals was significant. This was true for the randomized as well as the unchanged locations conditions.

Discussion

Empirical and theoretical views regarding locations have suggested that location is the most important cue in perceptual binding. The results of Experiments 1 and 2 suggest that this may only be true during the stimulus display and for a short period thereafter. When tested immediately after stimulus offset, unchanged locations resulted in almost ceiling performance for reporting shape and colour combinations.

When location was randomized, performance decreased substantially at 0 ms between study and test (though it was still above chance levels). Gradually, however, this disruption was overcome and randomizing location had no influence on performance.

One possible interpretation of the results is that consolidation of the bound object as a whole in VWM takes place over a period of more than 1000 ms. Once consolidated the objects are impervious to disruptions by a test display that has a very different spatial configuration from the study display. However, the consolidation of bound objects over such a long period of time is difficult to reconcile with estimates of time required for object identification or recognition, which are usually around 50 ms, and object differentiation (usually around 130 ms). Therefore, it seems extremely unlikely that the results reflect a gradual consolidation of whole objects.

Another account of the results is that an amalgamation of features occurs during the 200 ms stimulus display, and this initial, rapid integration into object representations includes location as well as colour and shape. At the shorter study-test intervals when the test display is shown in the randomized condition, so great is the mismatch between study and test displays that performance is severely disrupted. Therefore, the positive slope in the randomized locations condition simply reflects a gradually dissipating inhibition, such that the location information is suppressed to create refined object representations comprising only the combinations of colour and shape. Selective consolidation of relevant features and inhibition of the irrelevant features occurs concomitantly.

The initial rapid integration of features is clear in the unchanged locations condition. With none of the features being task irrelevant, there is no cause for inhibition in this condition. In fact, spatial attention and a location-reliant strategy, probably augments the participants' performance. The match of the test display with the iconic memory of the first display is also helpful in consolidating the overall pattern of the display, and in discerning swaps when they do occur. However, there does appear to be a loss of information over time. This probably reflects forgetting from a complex display that has more items than can be that can be transferred to or held in VSTM.

Forgetting over time may be happening in the randomized condition as well, but it becomes evident only after the randomization of location is no longer disruptive.

EXPERIMENT 3

Among the three features that are the focus of the present experiments, shape is a relatively stable property of an object. It allows an object to be identified regardless of its location, or changes in surface features such as colour. In contrast, location is often a transient property of an object, defining its momentary position in space rather than its permanent properties. Therefore, it is possible that location can be easily removed from a stimulus representation.

For many researchers in perception, form is as important as locations, if not more so. Early on, European psychology, including the Gestalt school, emphasized form to be fundamental to perception. Even today, despite the general emphasis on spatial attention, some theorists argue that form being distinct from spatial location, is at least as basic as location, and is certainly more important than colour or other surface features (Grossberg, 1997; Humphreys et al., 2000; Humphreys et al., 2009). Experiment 3 assesses the extent to which shape is required for forming and retaining bound representations in VWM.

Psychophysical studies reviewed in the beginning of this chapter suggest differential processing of various features. Physiological evidence also suggests that features such as colour and shape are processed via the ventral pathway whereas location is processed in the dorsal pathway (Ruchkin et al., 1997; Smith & Jonides, 1995; 1999; Funahashi et al., 2004; Trevarthen, 1968; Ungerleider & Mishkin, 1982). Thus, some difference in the pattern of results, i.e., the amount of disruption at the shorter study-test intervals is expected.

The dissociation between the ventral and dorsal processing streams might suggest that colour-shape bindings should be particularly strong given that these features are processed along the same (ventral) pathway and can define an object. In contrast, location allows the object to be detected initially in the stimulus display but might be much less relevant for defining a target object after it has been perceived. If colour-shape bindings in VWM are normally strong because they define an object, while location is not normally a defining feature of an object, then changing shape as a task-irrelevant feature might turn out to be even more disruptive of memory tested at longer study-test intervals than changing location.

There is ample experimental evidence that location and object identity appear to be processed separately in memory as well (Darling, Della Sala, & Logie, 2007; Jonides, Smith, Koeppe, Awh, Minoshima, & Mintun, 1993; Logie & Marchetti, 1991; Logie & van der Meulen, 2009), and indeed this is in line with the distinction between the visual and spatial aspects of the visuo-spatial sketchpad (Logie, 1995). Thus, differences in the experimental results might be expected when shape is randomized or colour is randomized in comparison to the unchanged conditions, even at longer study-test intervals, thus presenting a pattern quite dissimilar to that obtained in Experiments 1 and 2 where locations were randomized. However, this differential pattern in memory would suggest that features were still being processed separately in memory and were not consolidated and inhibited based on task relevance.

Contrarily, if the top-down factor of task relevance is indeed the overriding factor, (Proulx, 2007; Richard et al., 2008) then a pattern similar to Experiments 1 and 2 would occur when shapes or colours are randomized. Despite an initial difference in the unchanged and randomized conditions, gradually a convergence of performance would be shown, with task relevant features being consolidated as bindings, and shapes, being irrelevant, removed from the representations. This would be a post-perceptual process within VWM of inhibiting an irrelevant and unhelpful feature from the initial representation.

From the first two experiments, this process appears to take approximately 1500 ms for the randomized locations conditions. If shape is as crucial as location for bindings, then it might take a similar amount of time to remove it from the initial representation. However, if shape is not as crucial, then the interaction might occur earlier than for locations.

The task for the participants in this experiment was to detect a swap in colour-location binding. The stimuli being defined by three features, in the unchanged condition, a colour swap meant that the colour-shape and colour-location relationships changed, but the shape-location relationship did not change. Analogously, a location swap entailed a change in location-colour and location-shape relationships, but no change in the colour-shape relationship. In the randomized condition, when a change was made in any of the two target features, because the irrelevant feature randomly changed as well, the third dimension automatically changed. This implied a change in all three possible relationships, colour-shape, colour-location, and shape-location. Thus, there was a difference in the appearance of the test display in the unchanged condition, but not in the randomized condition as shown in Figure 5.3. It was possible that the type of swap would differentially affect performance in the unchanged and randomized shapes condition, even though the participant did not know beforehand about the type of swap. In fact, performance might show processing differences in the features involved. So it was planned that the difference between the types of swaps would also be tested separately in the unchanged and randomized conditions, the expectation being that location swaps would be easier to detect than colour swaps.

Participants

Twelve students (6 men and 6 women) in the age range 18-25 years participated and were given £10 as an honorarium.

Stimuli

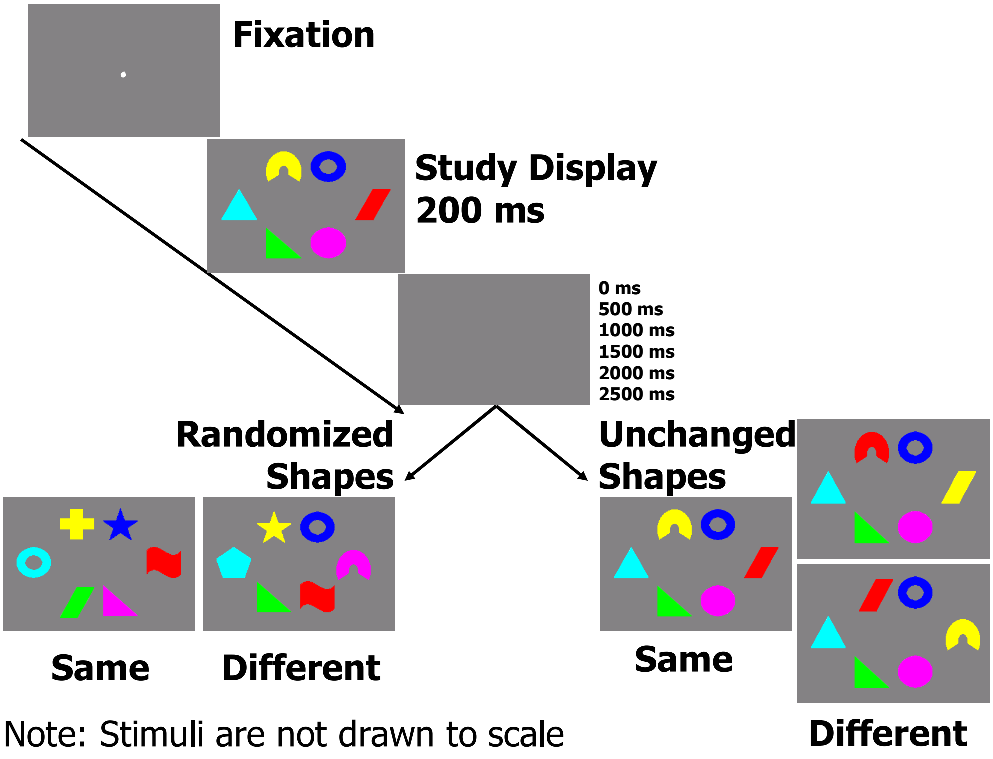
This experiment also presented six stimuli to the participant, but in six fixed locations in an invisible 3×4 grid of squares. The six colours were the same as Experiments 1 and 2 (cyan, yellow, magenta, red, green, blue). In each display, they were combined with any six of twelve shapes (circle, plus, right triangle, horseshoe, diamond, parallelogram, doughnut, star, wave, pentagon, triangle, trapezium) to form the stimuli.

Design and Procedure

The experiment was designed as a 2×6 factorial experiment with repeated measures on both factors. Figure 5.3 illustrates the procedure.

Figure 5.3

Sequence of events in Experiment 3



Note: Stimuli are not drawn to scale

The first independent variable was shapes manipulated at two levels: unchanged shapes vs. randomized shapes. In each trial six shapes were randomly chosen from a set of twelve shapes. In the unchanged shapes condition, all six shapes remained the same from study to test display. In the randomized shape condition six shapes were again randomly chosen (with replacement) from the set of twelve shapes for the test display and reallocated to different stimuli from study to test. Participants were asked to ignore the shapes and to remember the combinations of colour and location, for the task was to detect whether the location-colour binding had changed. The test display was different from the initial display on 50% of the trials. On these 'different' trials, the combination of colour and location was swapped randomly for any two items. In the unchanged shapes condition, on half of the ‘different’ trials, two stimuli swapped colour, whereas on the other half, two stimuli swapped locations. In the randomized shapes condition, swapping one feature implied swapping the other too. Study-test intervals of 0, 500, 1000, 1500, 2000, and 2500 ms were chosen as the six levels of the second independent variable. Other procedural details were the same as Experiment 2.

Results

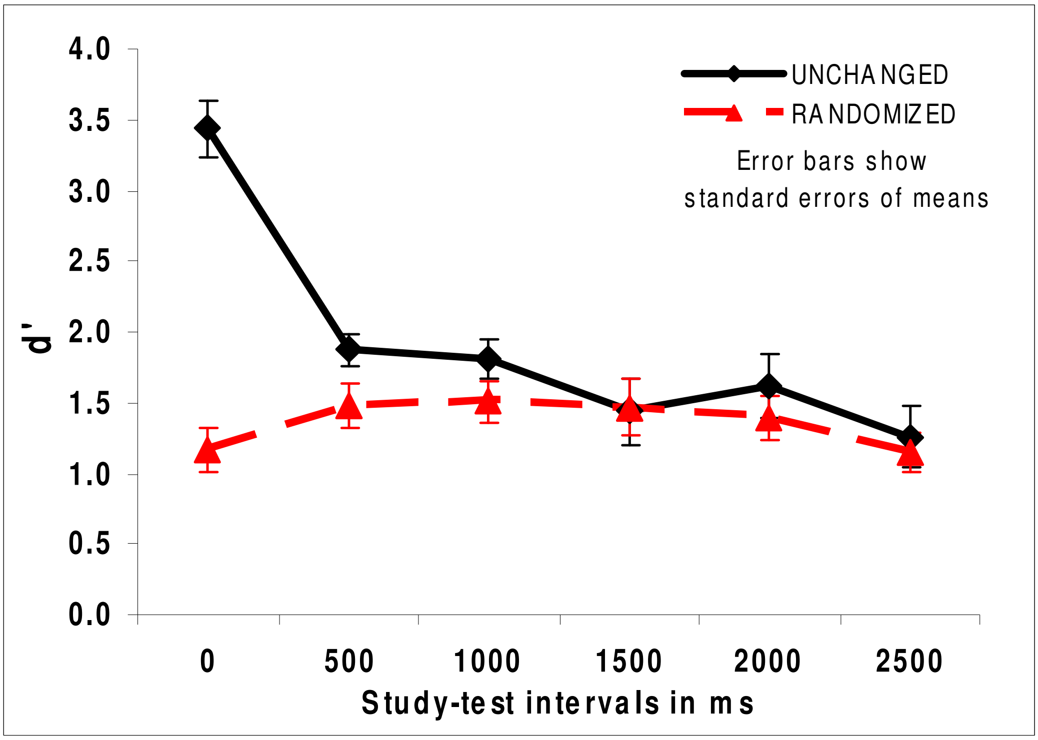
Mean change detection performance calculated from d-primes across study-test intervals for unchanged shapes and randomized shapes is shown in Figure 5.4. The main effect of shape condition was reliable, $F(1,11)=24.096$, $MSE=0.444$, $p<.001$, *partial* $\eta^2=.687$, in that, overall, memory for location-colour bindings was reduced when the shapes of the stimuli were randomized between study and test.

The main effect of study-test interval was also reliable, $F(2.744,30.189)=13.594$, $MSE=0.446$, $p<.001$, *partial* $\eta^2=.553$, with Greenhouse-Geisser correction, indicating that memory for location-colour bindings varied across study-test intervals. These factors interacted, $F(5,55)=24.105$, $MSE=0.183$, $p<.001$, *partial* $\eta^2=.687$.

As for previous experiments, the interaction was further investigated with separate single degree of freedom polynomial tests within each condition. In the unchanged shapes condition, performance across study-test intervals was characterized by a negative-slope linear $F(1,11)=46.931$, $MSE=.532$, $p<.001$, *partial* $\eta^2=.810$, quadratic $F(1,11)=30.468$, $MSE=.229$, $p<.001$, *partial* $\eta^2=.735$, and cubic $F(1,11)=20.213$, $MSE=.193$, $p<.001$, *partial* $\eta^2=.648$, trends. The significant higher order trends indicate that the rate of decrease in accuracy was not constant across all study-test intervals. In the randomized shape condition, only the quadratic trend, $F(1,11)=17.283$, $MSE=.084$, $p<.002$, *partial* $\eta^2=.611$, was reliable, indicating a curvilinear function. From Figure 5.4, it seems clear that randomizing shape between study and test is disruptive of memory for location-colour bindings at 0 ms, but at longer study-test intervals performance is not far below the level obtained in the unchanged condition.

Figure 5.4

Mean performance for unchanged and randomized shapes for each study-test interval in Experiment 3



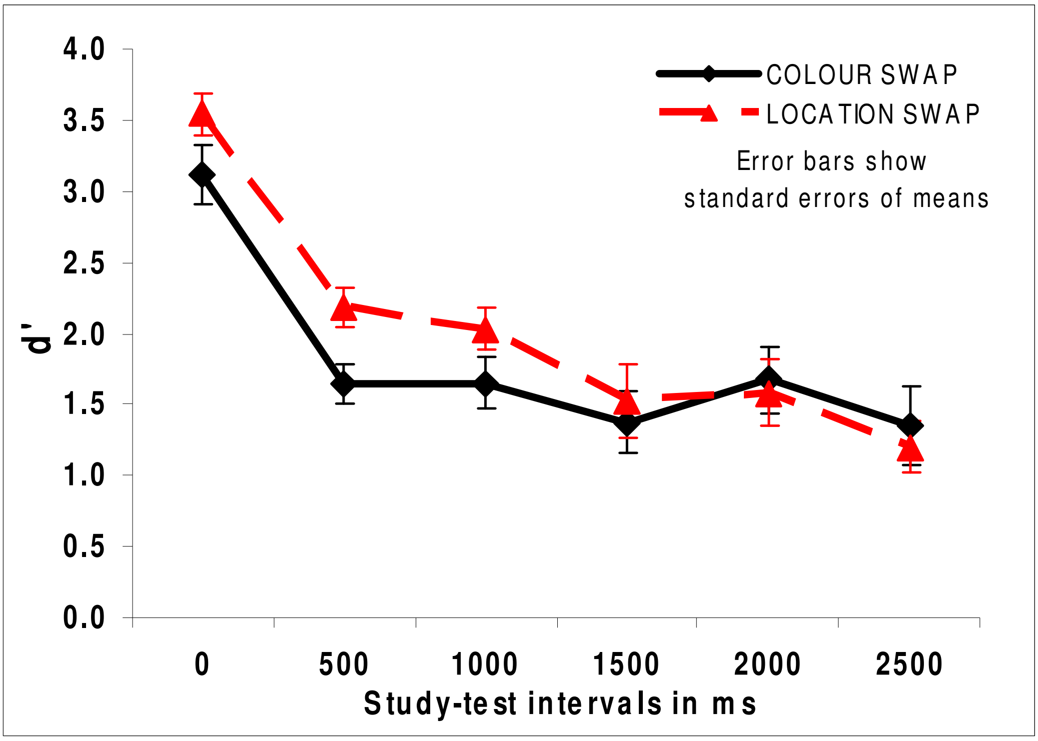
Planned comparisons using paired samples directional t tests with Bonferroni adjustment showed that the differences between the means for the unchanged and the randomized condition was significant at 0 ms $t(11)=11.703$, $p<.001$, and approached significance at 500 ms, $t(11)=2.561$, $p<.013$.

Comparing swaps

Additional analyses were done to test if the type of swap had any effect on the participants' performance. Analyses for swaps in the randomized shapes condition did not reveal any significant effects. Figure 5.5 shows the result of the unchanged shapes condition. There was a significant main effect of swaps, $F(1,11)=6.754$, $MSE=0.229$, $p<.025$ *partial* $\eta^2=.380$, overall, a location swap being detected more often than a colour swap. The was also a significant interaction between swaps and study-test intervals, *F*(5,55)=4.460, *MSE*=0.107, *p*<.002, *partial* η^2=.288.

Figure 5.5

Mean performance for location swaps and colour swaps with unchanged shapes for each study-test interval in Experiment 3



Planned comparisons using paired samples directional t tests with Bonferroni adjustment showed that location swaps were detected more often than a colour swap at 0 ms, *t*(11)=3.441, *p*<.003, and at 500 ms, *t*(11)=3.605, *p*<.002. Without Bonferroni adjustment, the difference was also significant at 1000 ms, *t*(11)=1.938, *p*<.039, again favouring location swaps. There were no significant differences thereafter. Separate single degree of freedom polynomial tests for each kind of swap showed similar trends for both kinds of swaps with negative slopes. For colour swaps, linear *F*(1,11)=25.672, *MSE*=0.548, *p*<.001, *partial* η^2=.700, quadratic, *F*(1,11)=19.628, *MSE*=0.349, *p*<.001, *partial* η^2=.641, and cubic, *F*(1,11)=16.479, *MSE*=0.256, *p*<.002, *partial* η^2=.600, trends were significant. Similarly, for location swaps too, linear *F*(1,11)=58.818, *MSE*=*0*.570, *p*<.001, *partial* η^2=.842, quadratic,

$F(1,11)=46.962$, $MSE=0.099$, $p<.001$, *partial* $\eta^2=.810$, and cubic, $F(1,11)=7.978$, $MSE=0.256$, $p<.017$, *partial* $\eta^2=.420$, trends were significant.

Discussion

It seems clear from this experiment that changing shape between study and test was disruptive of memory for location-colour bindings for short study-test intervals, but not for intervals of 500 ms or more. At these longer intervals, performance was identical to the unchanged condition. There was a tendency for performance to improve in the randomized condition between 0 ms and 500 ms, and to join the unchanged condition in showing forgetting as the study-test interval increases beyond 2000 ms. The pattern is broadly similar to that shown in Experiment 2 except that the initial level of disruption in the randomized condition is not so dramatic in Experiment 3. This has the consequence of leaving less scope for the improvement in performance with increasing study-test intervals, as found in Experiments 1 and 2.

In sum, results of Experiment 3 indicate that randomizing shape as a task-irrelevant feature is disruptive of change detection performance for location-colour bindings, but only at the shortest study-test interval of 0 ms. There is no reliable disruptive effect at intervals of 500 ms or more. This indicates that some initial bundling of shape, colour, and location occurs during stimulus presentation, and that shape as a task-irrelevant feature has to be removed during the process of forming a bound representation of location and colour in VWM. Once that representation has been formed, there is no impact of changing shape as a task-irrelevant feature.

When comparing these results to those in Experiment 2, it is clear that the disruptive effect of randomizing shape is less than the disruptive effect of randomizing location as a task-irrelevant feature. This might indicate that location does indeed have a powerful impact on the initial formation of bindings in visual perception. However, shape also makes a contribution to the initial binding even if it has a less dramatic disruptive effect when changed. There is then no strong evidence to support the idea that shape-colour binding would be any stronger than location-colour binding simply because colour and shape are both thought to be processed by the same ventral pathway. It is very striking however, that both shape and location result in disruption at shorter intervals, although they differ in initial, perceptual ‘binding potency’ and the disruptive influence of shape lasts for about 1000 ms less than the influence of location. In other words, shape has a lesser initial disruptive effect, and it takes less time to remove its effects than the effects of location.

EXPERIMENT 4

The motivation for Experiment 4 was broadly the same as for Experiment 3 except that here, the impact of randomizing colour between study and test was considered, to examine binding of location and shape. Colour being a property of the object processed in the ventral stream, whilst locations are processed in the dorsal stream, performance levels were expected to be different from Experiment 2. Also, in line with theoretical ideas that binding of form happens prior to binding of colours (Grossberg, 1995; Grossberg & Pessoa, 1998; Humphreys et al., 2000; Humphreys et al., 2009) and studies showing differences between ‘surface’ and ‘boundary’ features (Alvarez & Cavanagh, 2008) differences in the performance levels as compared to the Experiment 3 where shapes were made irrelevant were also anticipated, colour being a ‘surface’ feature and shape a ‘boundary’ feature. As reviewed in Chapter 2, developmental studies also hold binding of shapes to be primary as compared to colour (Needham,1999; Tremoulet et al., 2000) and so does evidence from experiments with real life pictures (Meng & Potter, 2008).

Thus, out of the three features that defined the stimuli, location, shape and colour, colour is seemingly least important. It was expected, therefore, that the disruption caused by randomizing colours would be lesser than that caused by randomizing shapes or locations. Nevertheless, it was also expected that the general pattern of results found in Experiments 2 and 3 would be replicated in terms of the interaction. Making colour irrelevant by randomization would be disruptive of performance as compared to the unchanged colours condition, to the extent that there would be a mismatch between the study and test display, but this disruption would reduce over time as the irrelevant feature of colour is removed from the representation in VWM, and only the shape-location bindings are selectively consolidated. Price and Humphreys (1989) showed that colours help object naming only if they are presented within the surface of the object, not when they form the background. Recent work by Lloyd-Jones and Nakabayashi (2009) indicated that this correct binding of shape and colour was not required for memory. They found that transforming the colour of an object reduced priming of coloured object decision making, suggesting that colour plays an important role in memory, but performance was similar whether the colour was presented within the shape of the object or appeared as the background to the object in gray scale. Together, the two studies suggest that correct colour-shape binding may be important in perception, but not in memory. Thus randomizing colour should be disruptive at the shorter but not the longer study-test intervals.

In the present experiment, the primary task was to detect a swap in shape-location binding. In the unchanged condition, a shape swap meant that the shape-colour and shape-location relationships changed, but the colour-location relationship did not change. A location swap meant a change in location-colour and location-shape relationships, but no change in the colour-shape relationship. Figure 5.6 clarifies this difference. In the randomized condition, when a change was made in any of the two target features, because the irrelevant feature randomly changed as well, the third dimension automatically changed. This implied a change in all three possible relationships, colour-shape, colour-location, and shape-location. Separate analyses in the unchanged and randomized conditions were planned to study if the differences between the types of swaps affected the performance of the participants, the expectation being that location swaps would be easier to detect than shape swaps, manifesting processing differences between these features.

Participants

Twelve students (6 men and 6 women) in the age range 18 - 25 years participated and were given £10 as an honorarium.

Stimuli

This experiment also presented six stimuli to the participant, in six fixed locations (as shown in Figure 5.6) in an invisible 3×4 grid of squares. The six shapes were the same as in Experiment 2 (circle, plus, right triangle, horseshoe, diamond, parallelogram) but they were combined with any six of twelve colours (cyan, yellow, magenta, red, green, blue, brown, dark green, dark blue, violet, white, and pink) to form the stimuli in each display.

Design and Procedure

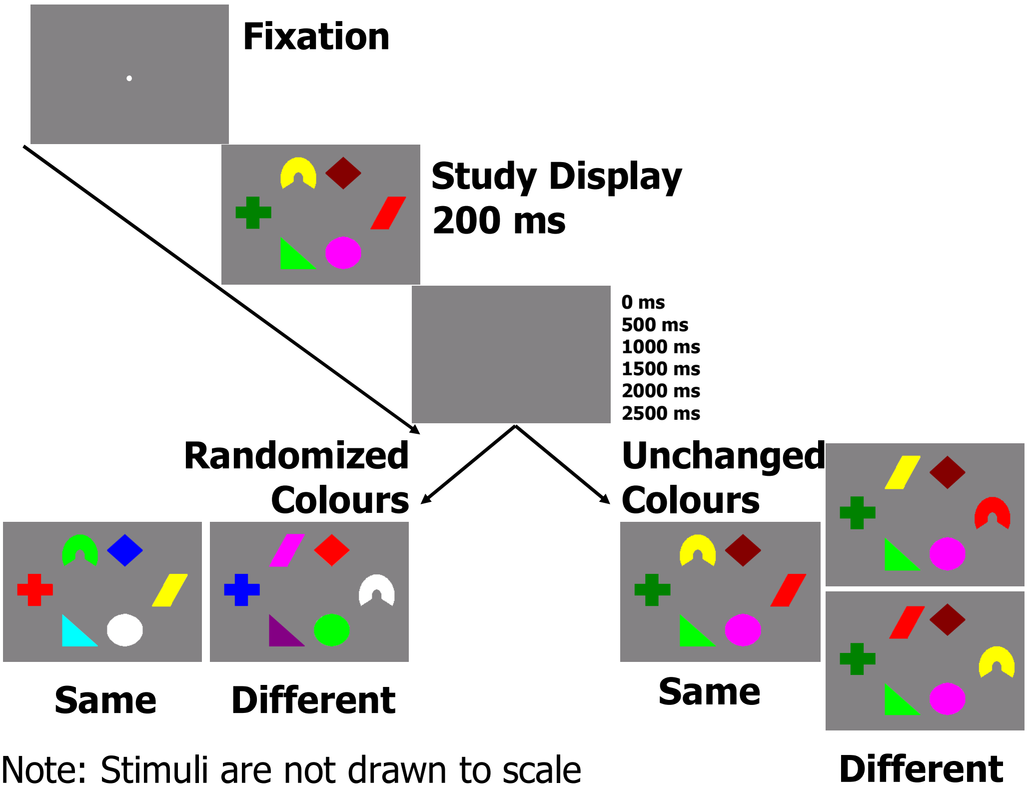
The experiment was a 2×6 factorial design with repeated measures on both factors. Figure 5.6 illustrates the design and procedure. The first independent variable was colours manipulated at two levels: unchanged colours vs. randomized colours. In each trial six colours were randomly chosen from a set of twelve colours. In the unchanged colours condition, all six colours remained the same from study to test display. In the randomized colours condition six colours were again randomly chosen (with replacement) from the set of twelve colours for the test display and reallocated to different stimuli from study to test. Participants were asked to ignore the colours and to remember the combinations of shape and location, the task being to detect whether the location-shape binding had changed.

The test display was different from the initial display on 50% of the trials. On these ‘different’ trials, the combination of shape and location was swapped randomly for any two items. In the unchanged colours condition, on half of the ‘different’ trials, two stimuli swapped shapes, whereas on the other half, two stimuli swapped locations. In the randomized colours condition, swapping one feature implied swapping the other too.

The second independent variable was the study-test interval manipulated at six levels, 0, 500, 1000, 1500, 2000, and 2500 ms, as in Experiments 2 and 3. Other procedural details were also the same as Experiments 2 and 3.

Figure 5.6

Sequence of events in Experiment 4



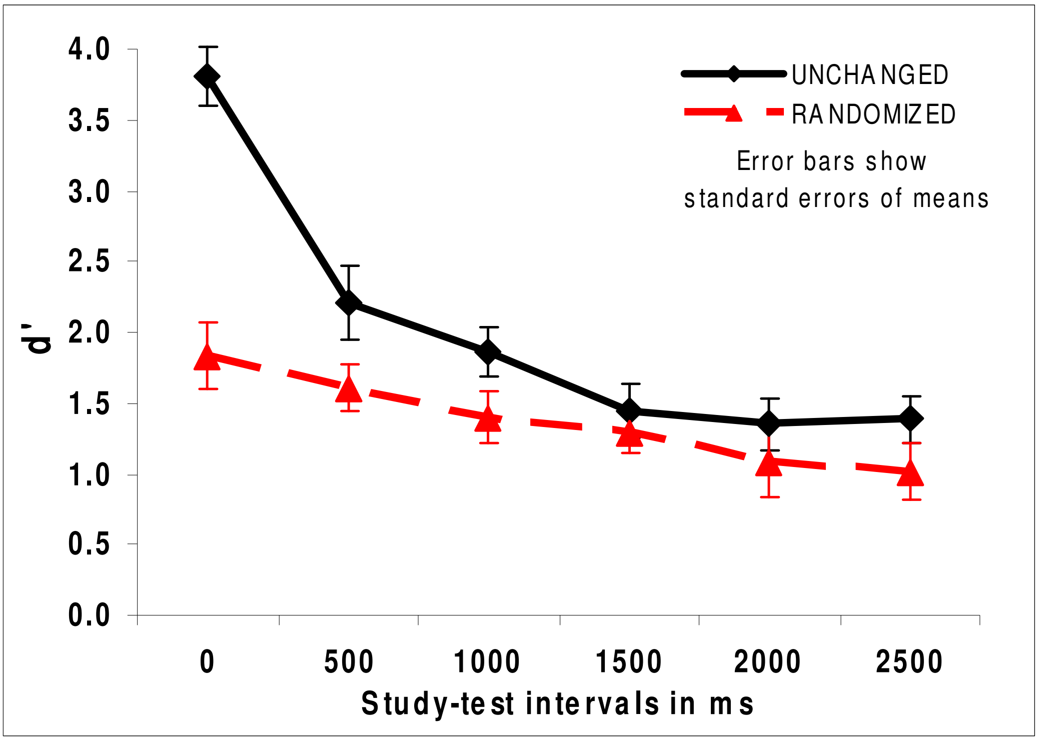
Note: Stimuli are not drawn to scale

Results

Mean change detection performance calculated from d-primes across study-test intervals for unchanged colours and randomized colours conditions is shown in Figure 5.7. The main effect of colour condition was reliable, $F(1,11)=23.573$, $MSE=0.627$, $p<.001$, *partial* $\eta^2=.682$, in that, overall, memory for location-shape bindings was reduced when the colours of the stimuli were randomized between study and test. The main effect of study-test interval was also reliable, $F(2.282,25.101)=35.548$, $MSE=0.559$, $p<.001$, *partial* $\eta^2=.764$, with Greenhouse-Geisser correction, indicating that memory for location-shape bindings varied across study-test intervals. These factors interacted, $F(5,55)=11.493$, $MSE=0.237$, $p<.001$, *partial* $\eta^2=.511$.

Figure 5.7

Mean performance for unchanged and randomized colours for each study-test interval in Experiment 4



Planned comparisons using paired samples directional t tests with Bonferroni adjustment showed that the differences between the means for the unchanged and the randomized condition was significant at 0 ms *t*(11)=9.074, *p*<.001, and approached significance at 500 ms, *t*(11)=2.333, *p*<.020, and 1000 ms, *t*(11)=2.129, *p*<.029.

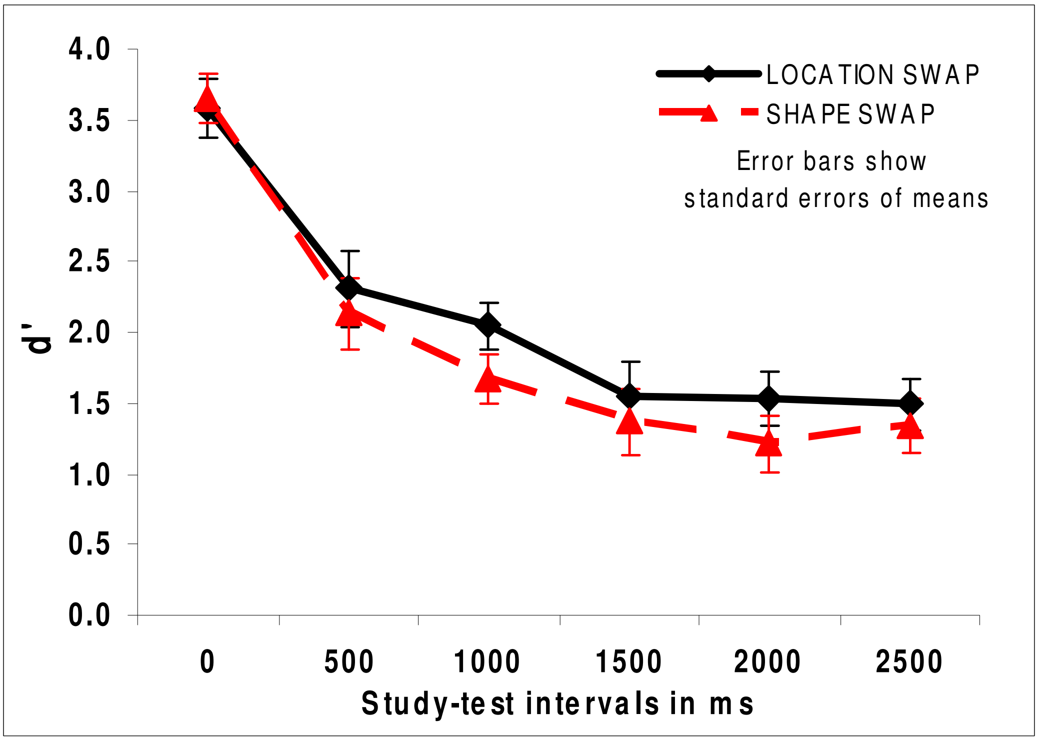
In the unchanged colours condition, single degree of freedom polynomial tests showed a negative slope linear, *F*(1,11)=92.285, *MSE*=.423, *p*<.001, *partial* η^2=.893, quadratic, *F*(1,11)=50.036, *MSE*=.241, *p*<.001, *partial* η^2=.820, and cubic *F*(1,11)=5.105, *MSE*=.259, *p*<.045, *partial* η^2=.317 trends. For the randomized colours condition as well, single degree of freedom polynomial tests showed a negative slope linear trend, *F*(1,11)=14.549, *MSE*=.389, *p*<.003, *partial* η^2=.569, this slope being shallower than that for the unchanged colours condition.

Comparing swaps

Analyses for types of swaps separately in the randomized and unchanged conditions revealed no significant difference in the randomized condition. In the unchanged condition, there was a significant main effect of swaps, $F(1,11)=6.569$, $MSE=0.193$, $p<.026$ *partial* $\eta^2=.374$, overall, a location swap being detected more often than a shape swap. Figure 5.8 shows the result of comparing swaps in the unchanged colours condition. The interaction between swaps and study-test intervals was not significant.

Figure 5.8

Mean performance for location swaps and colour swaps with unchanged shapes for each study-test interval in Experiment 4



Planned comparisons using paired samples directional t tests with Bonferroni adjustment showed that location swaps was detected more often than a colour swap at 1000 ms, $t(11)=2.896$, $p<.007$. Without Bonferroni adjustment, the difference was also significant at 2000 ms, $t(11)=2.288$, $p<.022$, again favouring location swaps.

Separate single degree of freedom polynomial tests for each kind of swap showed similar trends for both kinds of swaps with negative slopes. For colour swaps, linear $F(1,11)=104.199$, $MSE=0.353$, $p<.001$, *partial* $\eta^2=.905$, and quadratic, $F(1,11)=33.059$, $MSE=0.387$, $p<.001$, *partial* $\eta^2=.750$, trends were significant. Similarly, for location swaps too, linear $F(1,11)=62.573$, $MSE=0.484$, $p<.001$, *partial* $\eta^2=.850$, and quadratic, $F(1,11)=40.685$, $MSE=0.178$, $p<.001$, *partial* $\eta^2=.787$, trends were significant.

Discussion

Randomizing colours as a task-irrelevant feature between study and test was disruptive of memory for location-shape bindings for the study-test interval of 0 ms but not thereafter. This early stage disruption was much less than that observed for randomizing locations or randomizing shapes in Experiments 2 and 3. Even for the 0 ms study-test delay, performance in the randomized colour condition is higher than it is for longer delays in both the randomized colour and in the unchanged colour conditions. Though the disruptive effect of randomizing colour is less than that for randomizing location or shape in the earlier experiments, the convergence of performance levels between the unchanged and randomized conditions still appeared. The gradual suppression of the disruption caused by the task-irrelevant feature remains clear as the study-test interval increases. The results also suggest that colour (and shape) are less strong as features than location, and it takes less time to remove them from the initial stimulus representation in VWM than it does to remove location.

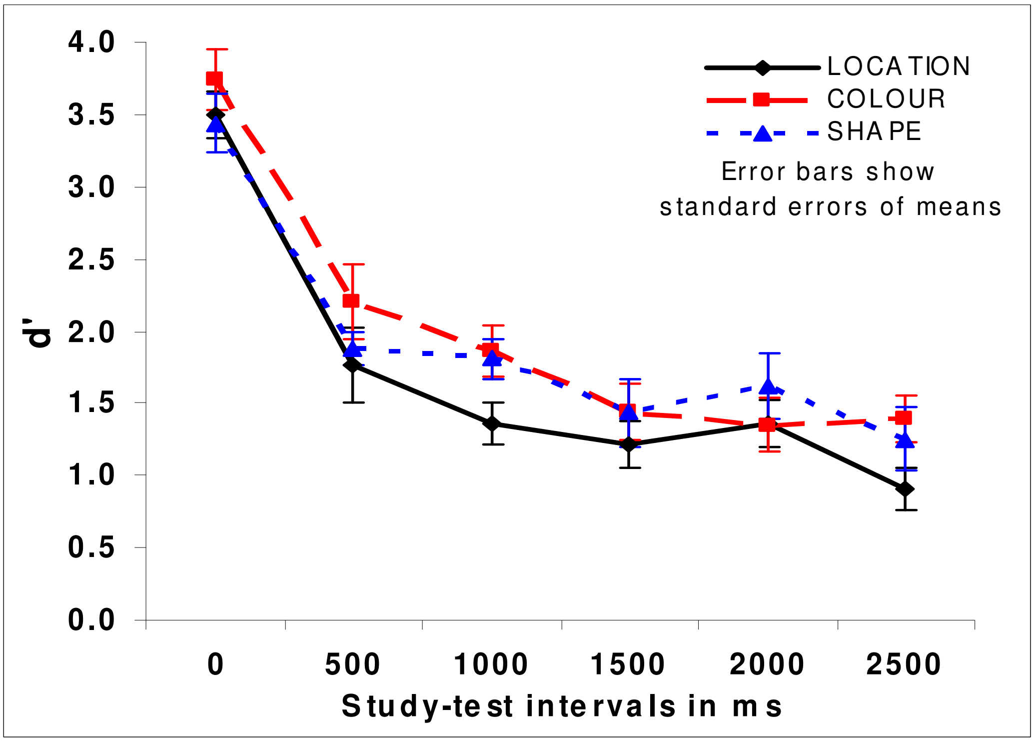
COMPARING EXPERIMENTS 2, 3, AND 4

A 3×2×6 ANOVA with features (between subjects), unchanged/randomized conditions (repeated measures), and study-test intervals (repeated measures) was carried out to compare Experiments 2, 3, and 4. The three-way interaction was not significant, nor was the two way interaction between unchanged/randomized condition and features. However, there were significant two way interactions between unchanged/randomized conditions and study-test intervals, *F*(5,10)=65.033, *MSE*=0.216, *p*<.001, *partial* η^2=.663, and between study-test intervals and features, *F*(10,165)=3.152, *MSE*=0.217, *p*<.001, *partial* η^2=.160. The main effects were significant for unchanged/randomized conditions, *F*(1,33)=90.728, *MSE*=0.559, *p*<.001, *partial* η^2=.733, and study-test intervals, *F*(3.179,104.900)=70.253, *MSE*=0.341, *p*<.001, *partial* η^2=.680, with Greenhouse-Geisser correction; and features, *F*(2,33)=3.841, *MSE*=1.975, *p*<.032, *partial* η^2=.189.

Two way ANOVAs were also conducted separately under unchanged and randomized conditions. Figure 5.9 depicts the result of the 3×6 ANOVA for the

Figure 5.9

Mean performance for unchanged features
for each study-test interval in Experiments 2, 3, and 4



unchanged condition with features as between subjects variable and study-test intervals as within subjects variable.

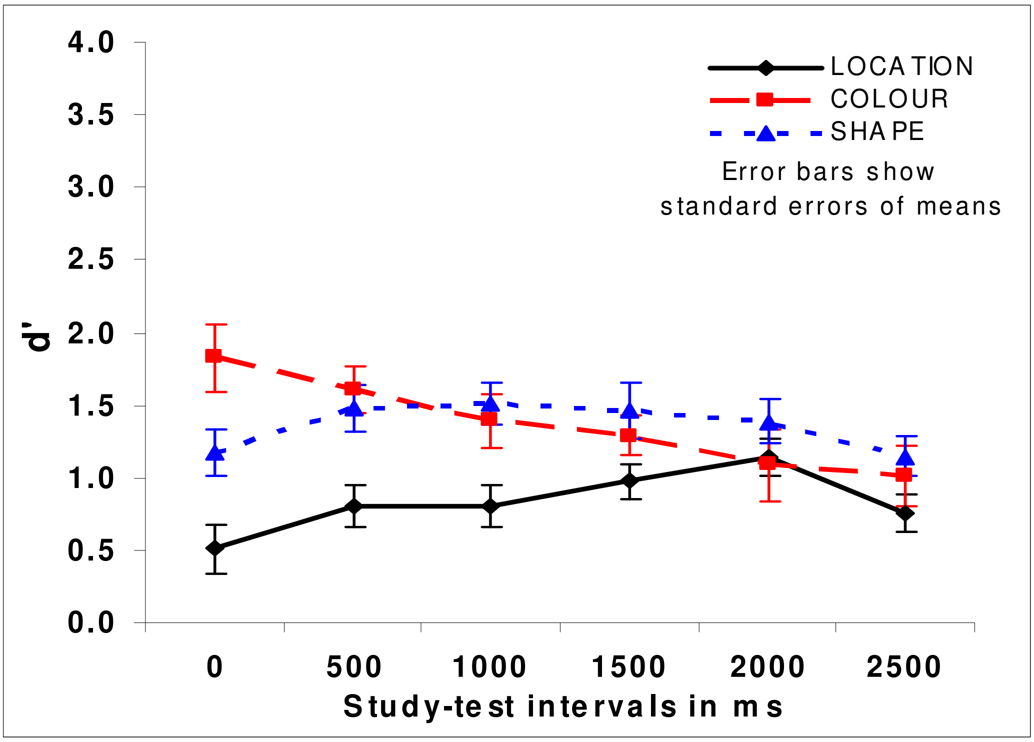
There was a significant main effect only for study-test intervals, *F*(5,165)= 115.667, *MSE*=0.249, *p*<.001, *partial* η^2=.778. Neither the main effect for feature, nor its interaction with study-test intervals was significant. As Figure 5.9 clarifies, the slope for all three features is similar and negative.

Figure 5.10 depicts the result of the 3×6 ANOVA for the randomized condition with features as between subjects variable and study-test intervals as within subjects variable.

Figure 5.10

Mean performance for randomized features

for each study-test interval in Experiments 2, 3, and 4



There was a significant main effect for feature, *F*(2,33)=6.051, *MSE*=1.127, *p*<.006, *partial* η^2=.268. Pairwise comparisons with Bonferroni correction showed significantly lower performance when locations were randomized as compared to shapes as well as colours, with no significant difference between shapes and colours. The main effect for study-test intervals was also significant, with Greenhouse-Geisser correction applied, *F*(3.780,124.744)=2.586, *MSE*=0.243, *p*<.043, *partial*

η^2=.073. There was also a significant interaction between the two variables, *F*(10,165)=4.179, *MSE*=0.184, *p*<.001, *partial* η^2=.202. Figure 5.10 clarifies that the interaction is driven by the difference between the features at the shorter study-test intervals and the difference in the slopes of the trends.

Single degree of freedom polynomial tests for each feature showed that for randomized locations, performance was characterized by a positive-slope quadratic trend, *F*(1,11)=7.114, *MSE*=.156, *p*<.022, *partial* η^2=.393. For randomized shapes, the quadratic trend, *F*(1,11)=17.283, *MSE*=.084, *p*<.002, *partial* η^2=.611, showed the curvilinear function. For randomized colours there was a negative-slope linear trend, *F*(1,11)=14.549, *MSE*=.389, *p*<.003, *partial* η^2=.569.

GENERAL DISCUSSION

In three experiments, the extent to which relevance of location, colour, and shape contributes to bindings of these features in perception and memory was examined. It is clear from these experiments that designating one feature as irrelevant and then randomizing it between study and test is disruptive of performance between the other two features at shorter, but not at longer study-test intervals. Results also showed that all features play a differential role in initial phases of binding. When task-irrelevant, locations were not important after 1500 ms, nor were colour and shape after 500 ms.

Indicating the role of bottom-up processes, the results suggest that features are processed at different rates in VWM. Location seems to be the most important feature because randomising location disrupts performance at the shorter study-test intervals to a greater extent than randomising colours or shapes. The participants also take more time to reach the point when location ceases to be relevant for processing. This indicates that location is a more difficult feature to ignore than colour or shape. The improvement in performance with increasing study-test intervals when locations are randomized also seems to be unique to locations, for no similar enhancement is found when colour or shapes are randomized.

Finding a swap in two dimensions, whilst a third also changes, is certainly a more difficult task as compared to finding a swap when the third dimension remains unchanged. But the difficulty level varies with the dimensions that change. This condition clearly demonstrates the differential processing of features. At 0 ms, performance is lowest when locations need to be ignored, better when shapes are to be ignored, and best when colours are to be ignored. Colours are easiest to ignore, whilst locations are the most resource demanding, with shapes somewhere in between. In fact so hard it is to ignore locations that performance is actually lower at the initial study-test intervals than the later ones. Gradually however, the three trends converge as the top-down WM processes presumably filter out the irrelevant information and retain only the relevant features as bindings.

The results of the additional analyses for different types of swaps corroborate that location is a special feature because changes in location are apt to be better detected than changes in other features, i.e., colour and shape in these experiments, when all other stimuli in the display remain unchanged. Analyses in the condition where the features are unchanged illustrates the relative importance of features in terms of what is to be remembered, i.e., the target swap to be remembered. The score in this condition is a composite of two distinct possibilities in each experiment. When location is held same, the target stimuli may swap either colour or shapes. When shape is held same, the change may be either in colour or locations. When colour is held same, the target stimuli may swap either shapes or locations. The difference is not significant for shape swap and colour swap, but location swap is easier to remember as compared to colour swap, as well as a shape swap.

The significance of non linear trends is indicative of the differences in the general performance of the participants at different stages across the study-test intervals in these experiments. Perhaps this implies that the initial stimulus representation is giving way to the development of an object but not in a gradual monotonically increasing way, and that there are factors, which may potentially affect the retrieval of bindings or the development of objects at each stage denoted by the different study-test intervals.

The fact that the greatest disruption to performance by randomizing irrelevant feature values between study and test occurs when the test display is presented immediately following stimulus offset suggests that the initial representations comprise both task-relevant and task-irrelevant features. Therefore, the test display fails to match any items in the representation of the study display, and this causes the poorer detection of changes in the pairing of task-relevant features between two objects.

The apparent improvement in performance with increasing study-test interval when locations were randomized in Experiments 1 and 2 appears to be unique to locations, for this was very weak with shapes in Experiment 2, and non-existent with colours. However, the increase in performance could be driven by the much greater disruptive effect of randomizing location at short study-test intervals. Performance in the unchanged condition after 1500 ms most likely represents the highest level of performance that can be obtained after that study-test interval, regardless of whether or not there was a disruption in the interim. Therefore, only the low performance at 0 ms in the randomized locations condition offers the scope to show a clear increase to the maximum level possible at 1500 ms.

What is critical is not whether performance improves in the randomized conditions, but that performance levels between the unchanged and the randomized conditions converge as study-test intervals increase. This convergence is clear in the interactions observed in all four experiments and indicates that the study-test interval chosen in any particular study of feature bindings has a fundamental impact on the pattern of results observed.

A possible account for the interactions between the randomized and the unchanged conditions over study-test intervals is that as the iconic trace decays, the more performance is reliant on bindings being formed between only the task-relevant features in VWM. The representation in VWM then allows a closer match for comparison with the combinations of task-relevant features in the test display, and therefore there is less of an impact of the randomization of the irrelevant feature. Object representations involving shape-location bindings are formed most easily or are the strongest, followed by colour-location bindings, followed by shape-colour bindings. After 500 ms when shape and colour were task-irrelevant and after 1500 ms when location was task-irrelevant, the process of forming task-relevant bindings as object representations in VWM is complete, and the task-irrelevant feature becomes irrelevant for performance as well. However, the difference in the rate of processing in the three features under consideration makes an explanation based solely on iconic decay rather less plausible, unless substantial assumptions regarding selection within the icon are made.

The initial differential processing of features is supported by physiological evidence (Aymoz & Viviani, 2004; Lamberts, 2002, Moutoussis & Zeki, 1997, Zeki et al., 1991) as well as psychophysical studies (Magnussen, 2000; Magnussen & Greenlee, 1997; Magnussen et al., 1996). Processing disparities suggest that features are bound at different rates and are thus being selectively processed. Differential processing of colour has been similarly interpreted as selective consolidation of features by Woodman and Vogel (2008), and indeed, has been linked to WM capacity. The much greater disruption of performance due to randomization of locations than shapes or colours supports the assertion that locations are special when compared to other features (Treisman, 1998). However, it is also true that over time, it is possible to ignore locations, just as it is possible to ignore colours or shapes. As suggested by Duncan (1998, 2006), task relevance is the top-down factor of overriding importance. Though his focus is on objects rather than features, it appears that task relevance affects differential processing of features as well, and the irrelevant features are 'biased out'. Hommel (2004) has also proposed that task relevance is the primary factor affecting binding.

The overall pattern of results is best explained by a confluence of ideas regarding bottom-up and top-down processing, such as those by Muller and Krummenacher who give a feature based account (Muller & Krummenacher, 2006a, 2006b) yet acknowledge that the weights assigned to features might be modulated by top-down factors (Muller et al., 2009). The present experiments have delineated a time course for this adjustment of weights according to task relevance. It appears that the differential effect of features is driven largely bottom-up and is thus evident at the shorter study-test intervals, but in the workspace of VWM (Logie, 2003) all features are treated in a similar way. They are consolidated if relevant, and discarded if irrelevant. Further, in accordance with task instructions, participants can only gradually consolidate relevant information and inhibit irrelevant information expending time and effort on this process. The nature of the mechanism, which aids this process, is the focus of the next chapter.

CHAPTER 6

EXPERIMENTS 5, 6, AND 7

In the set of experiments reported in this chapter, it was of interest to study how far consolidation of relevant features, and inhibition of irrelevant ones, can happen with a change in the nature of attention and top-down inputs at various study-test intervals. Experiments 5, 6, and 7 were designed to be analogous to Experiments 2, 3, and 4. The only difference was that the study-test intervals were randomly mixed on every trial within a block, and the participant had no information regarding the length of the study-test interval in each trial. This manipulation precluded the build up of any differential strategies by the participants before the start of the trial for shorter and longer study-test intervals (though it did not prevent them from using strategies within the trial). On the other hand, mixed presentation requires continuous shifts in focus before and within the trial, and requires intra-trial as well as inter-trial processing.

Blocked vs. mixed presentation is a simple way of testing the interaction of top-down strategic processes with transient processing effects that occur trial by trial. The point is not that one type of format is correct and another is incorrect. Rather, the point is that participants' mental activity is sensitive to format of presentation. Some researchers in the area of binding have used blocked presentation (e.g., Treisman & Zhang, 2006) while others have used mixed presentation (e.g., Woodman & Vogel, 2008), but the two have not been directly compared. Nevertheless, there is some related evidence in literature regarding the effects of these presentation formats on other performance measures.

One such comparison between blocked versus mixed designs was made by Ballesteros, Reales, and Manga (2000) who studied the effect of eight levels of word fragmentation on inhibition and facilitation observed in the Stroop task. They found that inhibition and facilitation effects showed up even at the most fragmented level in the blocked design, whereas only inhibition showed up in the mixed design, and facilitation disappeared. Thus they concluded that performance in the blocked condition reflected the operation of an expectancy or mental set that allowed implicit processing, whereas in the mixed design, performance was contingent only on explicit and/or semantic processing. Martens and Johnson (2005) tested if the attentional blink can be reduced if the time interval between the two stimuli is known in advance. Neither giving the trials in blocks, nor mixing them randomly had any effect on performance. However, explicitly cueing the target onset asynchrony on every trial did reduce the attentional blink. In a study involving a paired associate recall task to be encoded using imagery vs. rote learning, Price, Hertzog, and Dunlosky (2008) found that participants performed better and rated the imagery strategy to be more effective when tested under blocked conditions as compared to mixed conditions. Further, the awareness of strategy effectiveness was more pronounced in younger (mean age 19) than older (mean age 69) adults.

Contrasting blocked vs. mixed presentation is much more prevalent in studies using physiological measures. Johnson, Nolde, Mather, Kounios, Schacter, and Curran (1997) demonstrated processing differences in recognition memory for old, new, and lure words due to blocked vs. randomized trials using ERP. In blocked conditions, old and lure items were processed differently, but in the mixed condition, they were processed in a similar way. Early fMRI researchers often used either blocked or mixed presentations. Comparing performance for recall and recognition, Donaldson and Rugg (1999) found that though different areas were activated under blocked conditions, the same areas were activated under mixed conditions, suggesting that under mixed conditions, it is difficult to maintain the functionally differential strategies used in blocked conditions. Mechelli, Price, Henson, and Friston (2003) compared the error variance to study the relative efficiency of blocked vs. mixed design using fMRI. They found that the early visual areas did not show differential error variance for the two kinds of presentation, but most areas in the visual cortex did show greater error variance with mixed presentation. Statistically, blocked presentation often results in contrasts that are more significant.

These studies confirm that performance in response to blocked presentation is better and more stable because of the operation of top-down mental set. Top-down processes associated with sets, goals, or strategies can be established and sustained across trials within a block; although it may be difficult to control and maintain a specific cognitive state for the whole period of each block. In this sense, blocked presentation is also prone to potential confounds such as rapid habituation, anticipation, or other strategy effects. In contrast, performance in mixed conditions reflects transient processing effects that occur within trials and is affected by bottom-up processes to a greater extent. With randomly intermixed trials, participants may rely more on perceptual details of each trial to discriminate between them.

Attention is the mechanism through which these top-down processes are implemented. But as reviewed in Chapter 2, attention is itself a complex concept and plays many different roles. Generalised attention may be more prevalent in blocked presentation, but mixed presentation requires specific focus on each trial, excluding interference from previous and subsequent trials. Slagter, Giesbrecht, Kok, Weissman, Kenemans, Woldorff and Mangun (2007) studied generalised and specialised components of attentional control in a combined fMRI design. The design allowed the study of higher order processes manipulated in blocked conditions, and the study of within trial, transient, or event related effects in mixed conditions; whilst also allowing a study of the interaction between the two. There were no differences in activation between blocked and mixed conditions when participants were asked to respond to either location cues or colour cues, even though different brain regions were activated in response to these cues. Nevertheless, additional activity in the sub-regions of the fronto-parietal control areas was found to reflect shifting of attention, irrespective of task relevant information. With a similar combined design, Engelmann, Damaraju, Padmala, and Pessoa (2009) studied the effect of cash incentive manipulated in blocks and spatial attention assessed by mixed trials within blocks in a Posner type visual search task. Detection performance increased with incentive value. fMRI analyses showed that incentive motivation enhanced evoked responses in several sites associated with attention. The observed effect of incentive motivation was greater during invalid than valid trials, and the authors suggest that this was possibly because motivation has a larger effect on reorienting than orienting of attention. If it is accepted that the cash incentive provided a top-down cognitive and motivational set, this study seems to provide interesting evidence for interactions between global and transient types of attention in the performance of a perceptual task, suggesting that global attention has an effect at later, but not earlier stages of information processing.

Despite the focussing of attention required within each trial, mixed presentation also requires switching mental set from trial to trial. In this respect it certainly requires a more rigorous use of WM resources due to continuous attention switching, which is one of the three primary functions of the attentional control system (Baddeley, 2007; Baddeley & Logie, 1999, Monsell, 2003). This actually requires the participants to be prepared for all conditions of the experimental task. One might expect that more rigorous use of attentional resources might lead to better *memory* performance with mixed presentation. The contextual interference effect (review by Magill & Hall, 1990) suggests that this is indeed true. When contextual interference is high (as in mixed presentation), performance is suppressed during acquisition, but enhanced in tests of memory or transfer. The effect holds in the verbal (Schneider, Healy, & Bourne, 2002) as well as motor domain (Shea & Morgan, 1979), and is often used in various training programs.

Explanations of the contextual interference effect suggest that better retention in mixed presentation is due to more intensive use of WM processes at the time of acquisition because the participants engage in reconstructive activity as they need to rehearse the task goal every time they are faced with a new trial (Lee & Magill, 1985) and need to use intra-task as well as inter-task processing (Shea & Zimny, 1988; Wright, Li, & Whitacre, 1992, Wright, Shea, Li, & Whitacre, 1992). Accepting that contextual interference is high in mixed condition as against blocked condition Li and Wright (2000) directly compared the attentional demands of mixed and blocked presentation using dual task methodology. The primary task was key pressing in which the participants had to press four keys in a sequence, according to timing requirements displayed on the screen. Auditory choice reaction time was the secondary task given either before the response to the primary task or in the inter-trial interval. In line with the contextual interference effect, they found lesser error in the blocked condition in the primary task at the time of acquisition, but lesser error in the mixed condition after retention intervals of 10 minutes as well as 24 hours. They also found much longer RT on the secondary task in the mixed conditions as compared to the blocked condition (though both generated significantly longer RTs compared with baseline RT performance). This was proof that the mixed condition was much more attention demanding. No differences were observed between the two conditions when the secondary task was given before the response or during the inter-trial interval, and thus the effects of global or within trial attention could not be separated.

There is considerable evidence (review by Wulf & Shea, 2002) that the contextual interference effect is not obtained for complex cognitive skills such as computer based problem solving in a distillery (De Croock & Van Merrienboer, 2007) or tasks in a fight simulator (Goettl, 1995). It is acknowledged that the effect is being used as the basis of hypotheses regarding feature binding possibly for the first time in this thesis, and thus the prediction is speculative. This is particularly true because the previous studies use longer time-periods and primarily assess performance on perceptual motor tasks, and the effect often does not emerge for complex cognitive tasks. Nevertheless, binding being a much less complex process might well show the contextual interference effect. For the present experiments, this would predict that performance would be superior at longer study-test intervals for mixed presentation than for blocked presentation.

Performance in Experiments 2, 3, and 4 was tested under blocked conditions. Experiments 5, 6, and 7 were designed to have mixed presentation of trials, to enable a comparison between blocked and mixed presentation. The expectation was that there would be differences in the levels of the performance of the participants due to these different formats of presenting the trials, specifically that performance with mixed presentation will be lower at the shorter study-test intervals, but higher at the longer study-test intervals in keeping with the contextual interference effect. No differential predictions were made for the randomized and unchanged conditions, because only study-test intervals were being mixed. However, the variable was entered in the analyses to explore its interactive effects.

Despite the above prediction regarding difference between the experiments, it was anticipated that the pattern of the overall result of Experiments 2, 3, and 4 would hold, and the interaction effect would be observed in each experiment. It was of particular interest to explore *when* the convergence of performance, which denoted that randomizing a feature no longer had a differential effect on performance, would be manifest. For this reason planned comparisons at each study-test interval were used to test the differences between performance under unchanged and randomized conditions. Analogously, the effects of types of swaps were also tested through planned comparisons to see if they too followed the results obtained in the earlier Experiments 2, 3, and 4.

In Experiments 2, 3, and 4, the six study-test intervals were presented in three blocks of 20 trials each, to sum up to 60 trials for each of the study-test intervals and 360 trials in all within each of the feature unchanged/ randomized conditions. Since it was desirable to have the same number of trials in the Experiments 5, 6, and 7, four trials for each of the six study-test intervals were given in a randomly mixed order within each block of 24 trials. Within each of the feature unchanged/randomized conditions, the total number of blocks was 15, so that there were 60 trials for each of the study-test intervals, and 360 trials in all. Note that only the study-test intervals were presented in a mixed order, and the feature unchanged/randomized condition was not mixed. In all experiments, each participant completed 720 trials for the entire experiment.

EXPERIMENT 5

This experiment tested the effect of unchanged and randomized location on shape-colour binding at study-test intervals ranging from 0 to 2500 ms. In keeping with

Experiments 1 and 2, an interaction was expected with disruption of performance due to randomizing locations at the shorter but not the longer study-test intervals.

Participants

Twelve students (6 men and 6 women) in the age range 18-25 years participated in the experiment and were given an honorarium of £10.

Stimuli, Design, and Procedure

The stimuli, identical to Experiment 1 and 2 were random combinations of six colours and six shapes, placed at random locations in an invisible 3×4 square grid. The experiment was a 2 (unchanged / randomized locations) × 6 (study-test intervals) factorial design with repeated measures on both factors. Participants were tested on two consecutive days at the same time of the day, half being tested with randomized locations, and the other half being tested with unchanged locations on the first day. There were 15 blocks of 24 trials in each experimental session. The six levels of the second variable (study-test intervals) – 0, 500, 1000, 1500, 2000, and 2500 ms, were randomly mixed within each block of 24 trials. A brief rest pause was enforced after every five blocks.

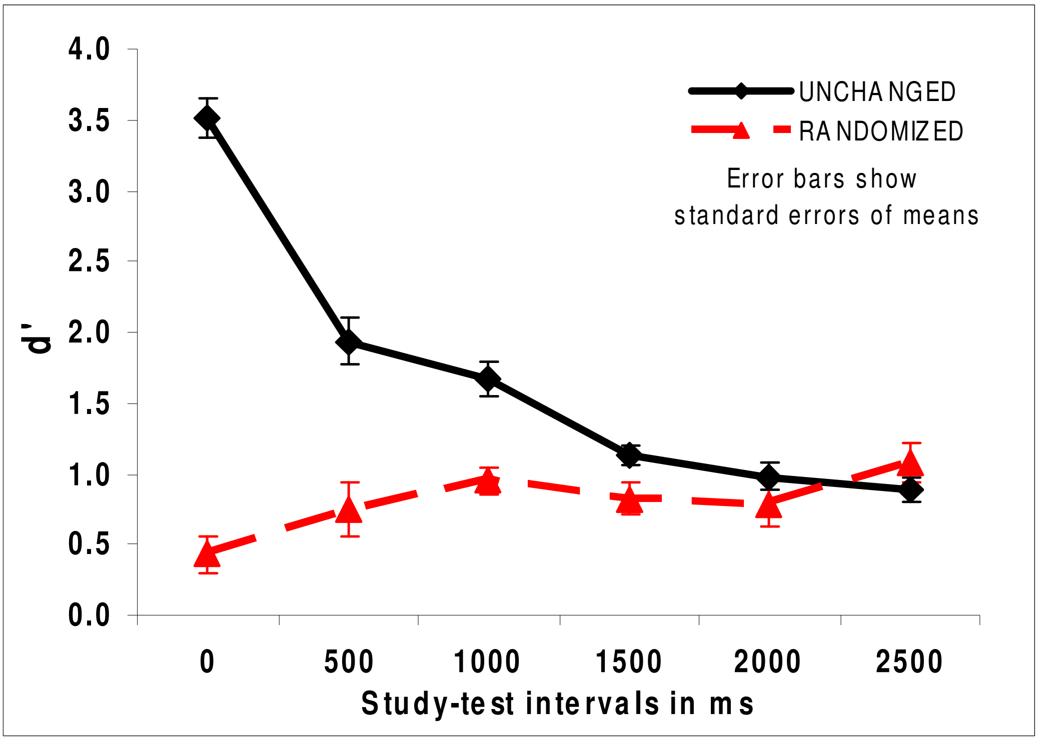
In each session, participants initially practiced six trials of each type of study-test intervals, starting from the longest study-test interval, and working gradually through all the study-test intervals to the shortest one of 0 ms, and then finished off with a block of 12 trials in which the six study-test intervals were mixed (as they were in the real experiment). Thus, in all they had 48 practice trials in each session, exactly as in Experiment 2. All other procedural details were the same as in Experiment 2.

Results

Mean change detection performance calculated from d-primes across study-test intervals and for the unchanged/randomized locations conditions is shown Figure 6.1. There was a significant main effect of locations conditions, $F(1,11)=46.974$, $MSE=.600$, $p<.001$, *partial* $\eta^2=.810$, showing that memory for bindings was significantly reduced when location of stimuli was changed between study and test. The main effect of study-test intervals was also significant, *F*(5,55)=30.557, *MSE*=.127, *p*<.001, *partial* η^2=.735 indicating that memory for bindings was significantly different across the study-test intervals chosen in this experiment. There was a significant interaction between these variables, *F*(5,55)=62.222, *MSE*=.133, *p*<.001, *partial* η^2=.850.

Figure 6.1

Mean performance for unchanged and randomized locations for each study-test interval in Experiment 5



Single degree of freedom polynomial tests for unchanged locations showed a negative slope linear trend, *F*(1,11)=245.114, *MSE*=.191, *p*<.001, *partial* η^2=.957, quadratic trend, *F*(1,11)=68.704, *MSE*=.129, *p*<.001, *partial* η^2=.862, and cubic trend, *F*(1,11)=7.809, *MSE*=.159, *p*<.017, *partial* η^2=.415. For randomized locations, single degree of freedom polynomial tests showed a positive slope linear trend,

$F(1,11)=17.800$, $MSE=.102$, $p<.001$, *partial* $\eta^2=.618$, and cubic trend, $F(1,11)=8.726$, $MSE=.089$, $p<.013$, *partial* $\eta^2=.442$. The significant higher order trends indicate a non-linear relationship between study-test interval and performance.

Planned comparisons using paired samples directional t tests with Bonferroni adjustment showed that the difference between the means for the unchanged and the randomized condition was significant at 0 ms, $t(11)=14.958$, $p<.001$; 500 ms, $t(11)=4.003$, $p<.001$; and 1000 ms, $t(11)=4.849$, $p<.001$, and approached significance at 1500 ms, $t(11)=2.240$, $p<.024$.

Comparing swaps

Additional analyses were done to test if the type of swap had any effect on the participants' performance. Analyses for swaps in the randomized locations condition did not reveal any significant effects. In the unchanged locations condition, though the main effect for swaps was not significant, the interaction between swaps and study-test intervals was significant, $F(5,55)=2.434$, $MSE=0.106$, $p<.046$, *partial* $\eta^2=.181$, as shown in Figure 6.2.

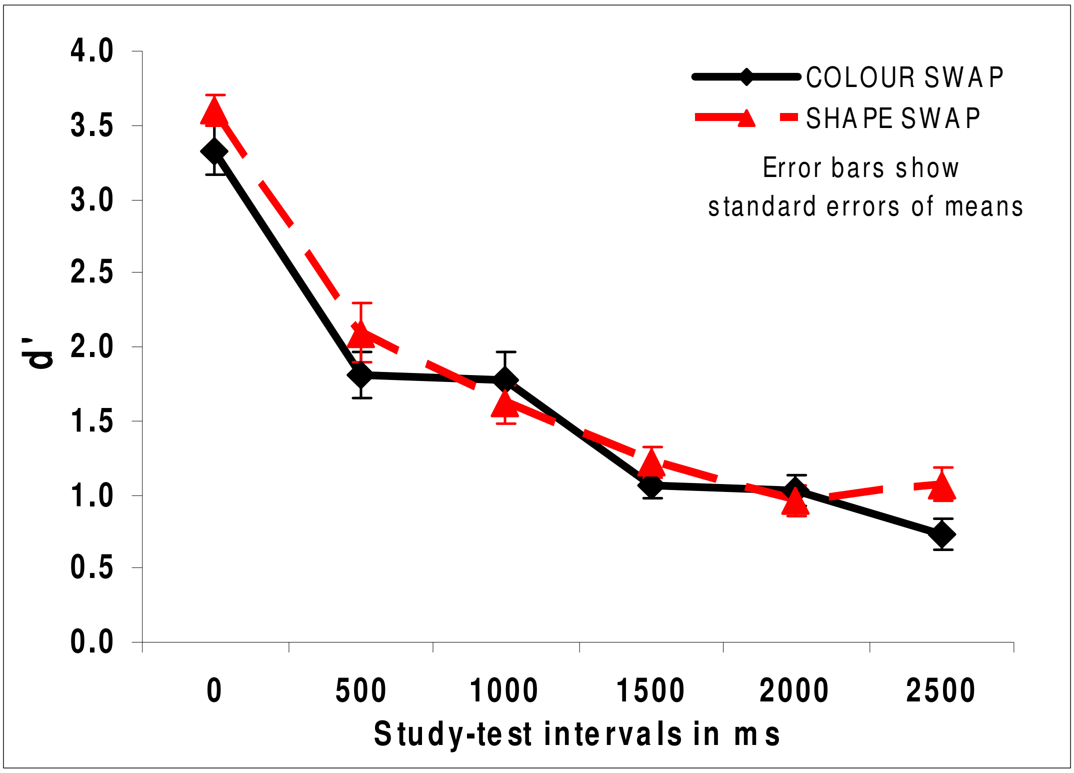
Planned comparisons using paired samples directional t tests with Bonferroni adjustment showed that shape swaps were detected more often than a colour swaps at 2500 ms, $t(11)=2.980$, $p<.005$. Without Bonferroni adjustment, the difference was also significant at 500 ms, $t(11)=2.481$, $p<.015$, again favouring shape swaps.

Separate single degree of freedom polynomial tests for each kind of swap showed the difference in trends for both kinds of swaps, though the slope was negative in each case. For colour swaps, linear $F(1,11)=244.090$, $MSE=0.180$, $p<.001$, *partial* $\eta^2=.957$, quadratic, $F(1,11)=37.528$, $MSE=0.143$, $p<.001$, *partial* $\eta^2=.773$, cubic, $F(1,11)=7.262$, $MSE=0.200$, $p<.021$, *partial* $\eta^2=.398$, and quintic, $F(1,11)=5.620$, $MSE=0.287$, $p<.037$, *partial* $\eta^2=.338$, trends were significant.

For shape swaps only the linear $F(1,11)=189.516$, $MSE=0.246$, $p<.001$, *partial* $\eta^2=.945$, and quadratic, $F(1,11)=72.070$, $MSE=0.160$, $p<.001$, *partial* $\eta^2=.868$, trends were significant.

Figure 6.2

Mean performance for shape swaps and colour swaps with unchanged locations for each study-test interval in Experiment 5



Comparing Experiments 5 and 2

A 2×2×6 ANOVA with experiments (between subjects), unchanged/randomized conditions (repeated measures), and study-test intervals (repeated measures) was carried out to compare Experiments 5 and 2. The three-factor interaction was not significant. The main effect for experiment was also not significant, nor was the interaction of experiment with unchanged/randomized condition.

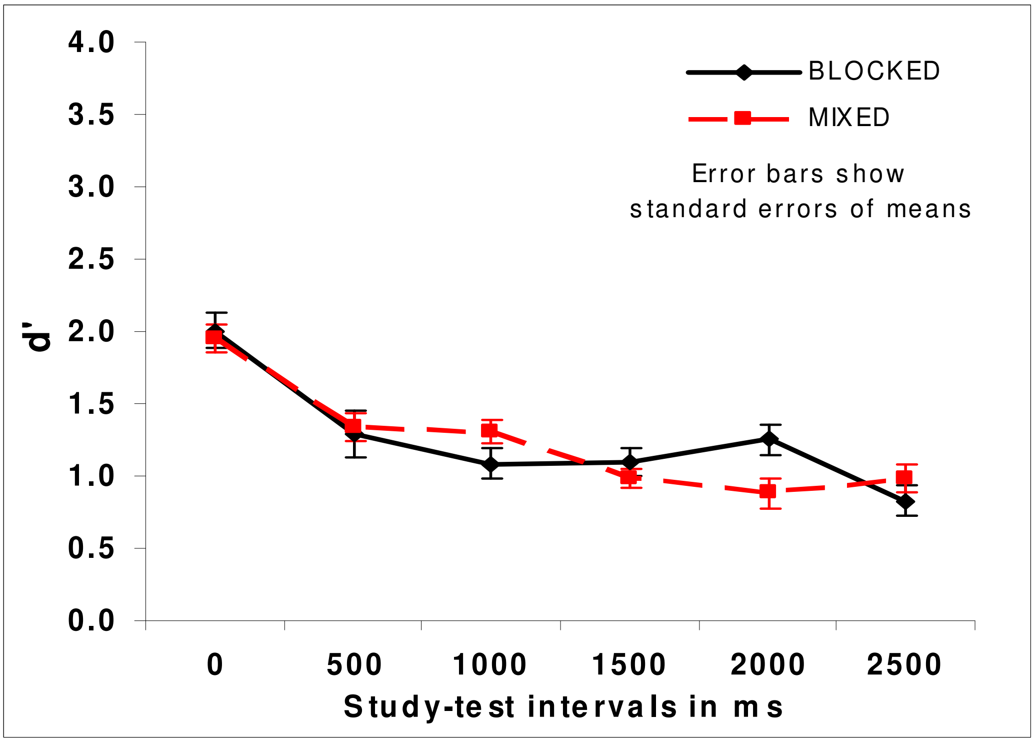
However, the interaction between experiments and study-test intervals was significant, $F(5,110)=3.913$, $MSE=0.139$, $p<.003$, *partial* $\eta^2=.151$, indicating that the performance of the participants differed in the two experiments across the various study-test intervals. Figure 6.3 shows this result.

Single degree of freedom polynomial tests showed negative slope reliable linear, $F(1,11)= 77.546$, $MSE=.086$, $p<.001$, *partial* $\eta^2=.876$, quadratic, $F(1,11)= 16.346$, $MSE=.087$, $p<.002$, *partial* $\eta^2=.598$, and cubic $F(1,11)= 66.796$, $MSE=.035$, $p<.001$, *partial* $\eta^2=.859$, trends for blocked presentation in Experiment 2.

For mixed presentation in Experiment 5, only the linear $F(1,11)= 70.364$, $MSE=.107$ $p<.001$, *partial* $\eta^2=.865$, and quadratic $F(1,11)= 31.134$, $MSE=.053$, $p<.001$, *partial* $\eta^2=.739$, trends were significant.

Figure 6.3

Mean performance for each study-test interval
with blocked (Experiment 2) and mixed (Experiment 5) presentation



Paired comparisons using independent samples t tests showed that the only significant difference occurred at 2000 ms, $t(22)=2.389$, $p<.0246$, favouring blocked presentation, but with Bonferroni adjustment this was not significant.

Discussion

From the results of Experiments 1 and 2, and the empirical and theoretical literature reviewed in Chapter 2, it was expected that randomizing location would interrupt performance at the shorter but not the longer study-test intervals. The results of Experiment 5 confirmed this prediction.

Differences between colour swaps and shape swaps occurred at 0 and 500 ms, favouring the detection of shape swaps, confirming that shape has a more important role to play in binding than colour. The comparison of blocked and mixed presentation used in Experiments 2 and 5 showed that blocked presentation aided performance at the longer study-test interval of 2000 ms, contrary to the expectation from the contextual interference effect. The possible reasons for this result are delineated in the general discussion of this chapter.

EXPERIMENT 6

This experiment studied the impact of randomizing shapes between study and test on the binding of locations and colours. In keeping with the results of Experiment 3, it was expected that performance will be disrupted due to randomization of shapes at the short but not the longer study-test intervals. From, Experiment 3, it was also expected that location swaps would be easier to detect than colour swaps in the unchanged shapes condition.

Participants

Twelve students (6 men and 6 women) between the ages of 18 and 25 years participated and were given £10 as an honorarium.

Stimuli, Design, and Procedure

Stimuli were the same as in Experiment 3. Six colours (cyan, yellow, magenta, red, green, blue) were combined with any six of twelve shapes (circle, plus, right triangle, horseshoe, diamond, parallelogram, doughnut, star, wave, pentagon, triangle, trapezium). In each trial six shapes were randomly chosen from a set of twelve shapes, randomly combined with six colours and presented in six fixed locations in an invisible 3×4 grid of squares.

The experiment was designed as a 2×6 factorial experiment with repeated measures on both factors. The first independent variable was shapes manipulated at two levels: unchanged shapes vs. randomized shapes. Participants were asked to ignore the shapes and to remember the combinations of colour and location, and the task was to detect whether the location-colour binding had changed. They were tested on two consecutive days at the same time of the day, half being tested with randomized shapes, and the other half being tested with unchanged shapes on the first day. There were 15 blocks of 24 trials in each experimental session. The six levels of the second independent variable (study-test intervals) – 0, 500, 1000, 1500, 2000, and 2500 ms, were randomly presented within each block of 24 trials. A brief rest pause was enforced after every five blocks.

In each session, participants initially practised six trials of each type of study-test intervals, starting from the longest study-test interval, and working gradually through all the study-test intervals to the shortest one of 0 ms, and then finished off with a block of 12 trials in which the six study-test intervals were given in a random order (as they were in the real experiment). Thus, they had 48 practice trials in total in each session, the same as in Experiment 3. All other procedural details were also the same as in Experiment 3.

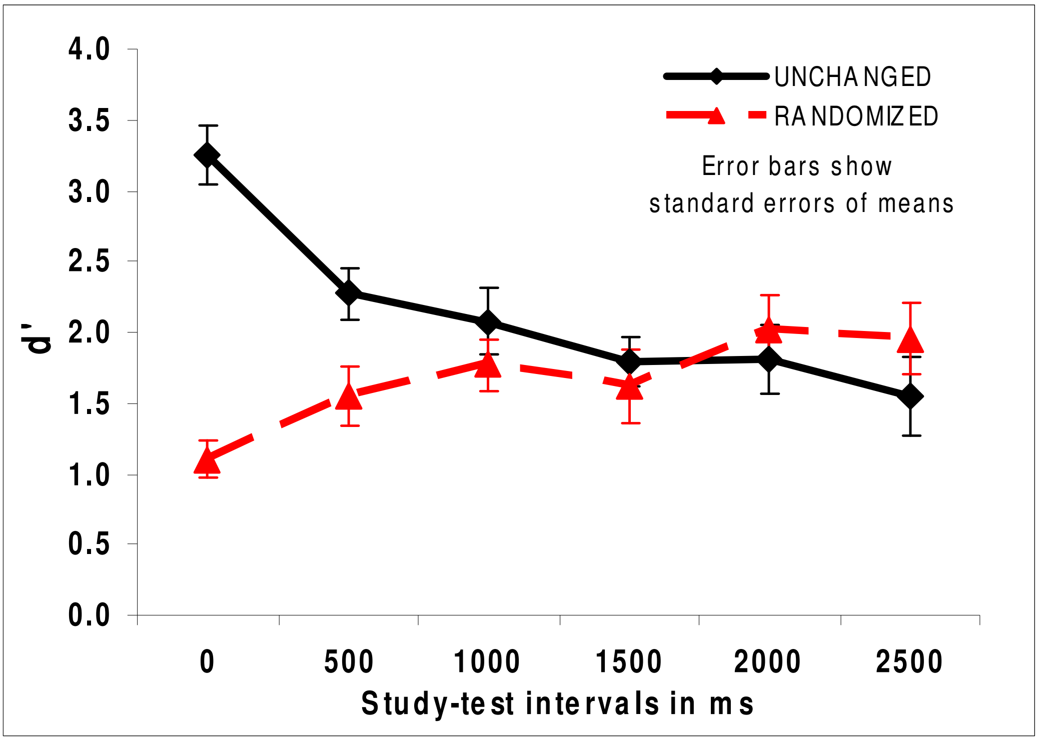
Results

Mean change detection accuracy across study-test intervals for unchanged shapes and randomized shapes conditions is shown in Figure 6.4.

There was a significant main effect of unchanged/randomized shapes, $F(1,11)=9.681$, $MSE=0.783$, $p<.010$, *partial* $\eta^2=.468$, in that memory for bindings was significantly reduced when shapes of stimuli were changed between study and test. The main effect of study-test intervals was also significant, *F*(5,55)=2.853, *MSE*=0.233, *p*<.023, *partial* η^2=.206, indicating that memory for bindings differed across the study-test intervals. The two variables interacted, *F*(5,55)=23.820, *MSE*=0.215, *p*<.001, *partial* η^2=.684. As study-test intervals increased, performance decreased in unchanged shapes condition, whereas it increased in the randomized shapes condition. Single degree of freedom polynomial tests showed a reliable negative slope linear trend, *F*(1,11)= 40.991, *MSE*=0.437, *p*<.001, *partial* η^2=.788, and quadratic trend, *F*(1,11)= 17.828, *MSE*=0.163, *p*<.001, *partial* η^2=.618, for unchanged shapes. For randomized shapes, only the linear trend, *F*(1,11)= 17.848, *MSE*=0.298, *p*<.001, *partial* η^2=.619, was significant, and it had a positive slope.

Figure 6.4

Mean performance for unchanged and randomized shapes for each study-test interval in Experiment 6



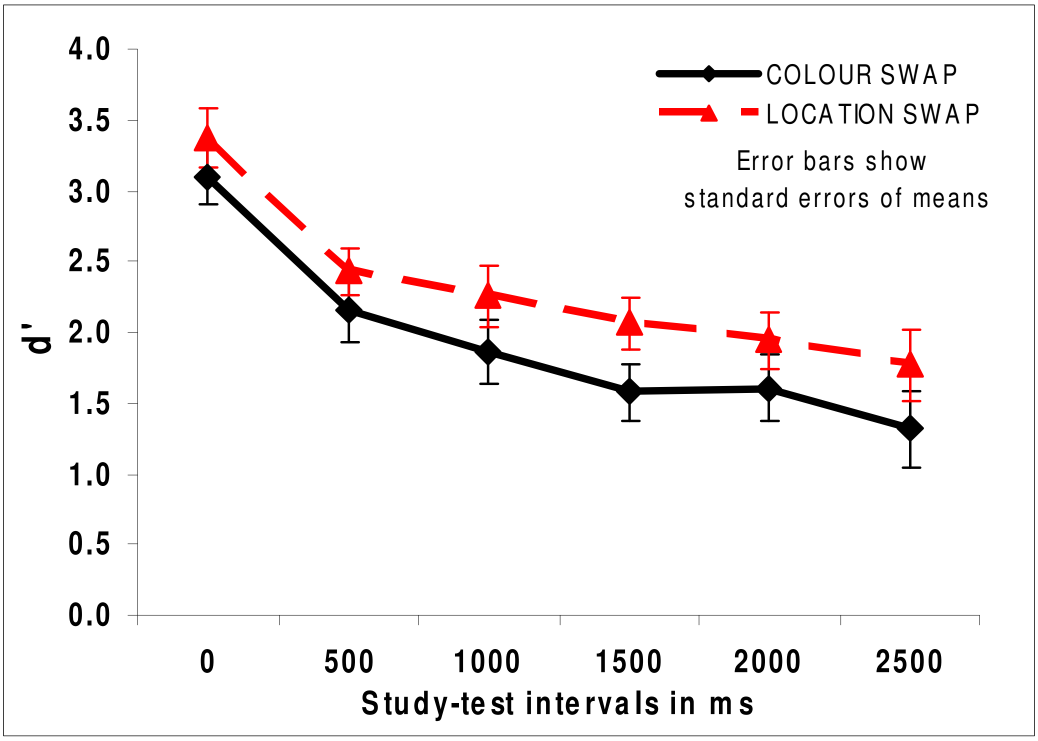
Planned comparisons using paired samples directional t tests with Bonferroni adjustment showed that the difference between the means for the unchanged and the randomized condition was significant at 0 ms, *t*(11)=8.297, *p*<.001, and 500 ms, *t*(11)=2.809, *p*<.008.

Comparing swaps

Analyses for swaps in the randomized shapes condition did not reveal any significant effects. However, in the unchanged shapes condition, there was a significant main effect of swaps, *F*(1,11)=48.871, *MSE*=0.101, *p*<.001, *partial* η^2=.816, location swaps being detected more often than colour swaps at all study-test intervals. Figure 6.5 shows this result.

Figure 6.5

Mean performance for location swaps and colour swaps with unchanged shapes for each study-test interval in Experiment 6



Planned comparisons using paired samples directional t tests with Bonferroni adjustment showed that the differences were reliable at 1000 ms, *t*(11)=4.193, *p*<.001, at 1500 ms, *t*(11)=3.247, *p*<.004; at 2000 ms, *t*(11)=3.285, *p*<.004, and at 2500 ms, *t*(11)=5.574, *p*<.001. The interaction between swaps and study test intervals was not significant. Separate single degree of freedom polynomial tests for each kind of swap showed similar trends with negative slopes for both kinds of swaps. For colour swaps, linear $F(1,11)=49.051$, $MSE=0.410$, $p<.001$, *partial* $\eta^2=.817$, and quadratic, $F(1,11)=16.723$, $MSE=0.179$, $p<.002$, *partial* $\eta^2=.603$, trends were significant. Similarly, for location swaps, linear, $F(1,11)=35.830$, $MSE=0.450$, $p<.001$, *partial* $\eta^2=.765$, and quadratic, $F(1,11)=11.969$, $MSE=0.196$, $p<.005$, *partial* $\eta^2=.521$, trends were significant.

Comparing Experiments 6 and 3

A 2×2×6 ANOVA with experiments (between subjects), unchanged/randomized conditions (repeated measures), and study-test intervals (repeated measures) was carried out to compare Experiments 6 and 3. The three-factor interaction was not significant. The main effect for experiment was also not significant, nor was the interaction of experiment with unchanged/randomized condition. However, the interaction between experiments and study-test intervals was significant, $F(5,110)=2.617$, $MSE=0.239$, $p<.028$, *partial* $\eta^2=.106$, indicating that the performance of the participants differed in the two experiments across the study-test intervals studied. Figure 6.6 shows this result.

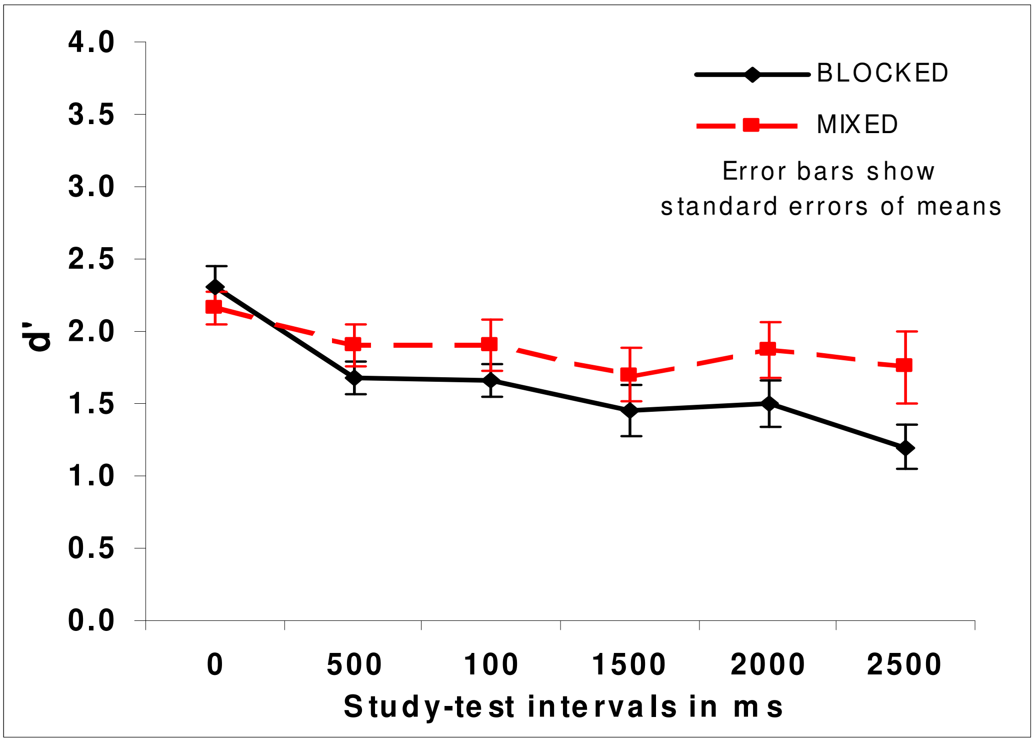
Paired comparisons using independent samples t tests showed that the only significant difference occurred at 2500 ms, $t(11)=1.897$, $p<.035$, favouring mixed presentation, but with Bonferroni adjustment this was not significant.

The significant interaction is better explained by the different nature of trends observed with the two kinds of presentation. Single degree of freedom polynomial tests showed negative slope linear, $F(1,11)= 26.014$, $MSE=0.259$, $p<.001$, *partial* $\eta^2=.703$, quadratic, $F(1,11)= 6.126$, $MSE=0.085$, $p<.031$, *partial* $\eta^2=.358$, and cubic, $F(1,11)= 6.809$, $MSE=0.117$, $p<.024$, *partial* $\eta^2=.382$, trends for blocked presentation in Experiment 3. For mixed presentation in Experiment 6, none of the trends was significant.

Figure 6.6

Mean performance for each study-test interval

with blocked (Experiment 3) and mixed (Experiment 6) presentation



Discussion

Changing shapes between study and test was disruptive of memory for location-colour bindings for the study-test intervals of 0 and 500 ms, but not thereafter. The pattern is similar to that shown in Experiment 3 except that here the difference between unchanged and randomized shapes is significant at 500 ms as well, and thus the convergence of performance happens later. The analyses of swaps confirmed the importance of locations as a special feature by showing that location swap is easier to remember as compared to colour swaps in the unchanged shapes condition.

The comparison of blocked and mixed presentation used respectively in Experiments 3 and 6 showed an interaction effect, following the prediction from the contextual interference effect that performance would be lower at shorter study-test intervals but higher at the longer study-test intervals with mixed presentation. Though the gradual divergence of performance in the two conditions is clear from the graph, the difference significantly favoured mixed presentation only at the longest study-test interval.

EXPERIMENT 7

In this experiment the impact of randomizing colour between study and test was considered on the binding of location and shape. From the results of Experiment 4, it was expected that performance would be disrupted due to randomization of colour at the shorter but not the longer study-test intervals. It was also expected that location swaps would be better detected than shape swaps in the unchanged colours condition.

Participants

Twelve students (6 men and 6 women) between the age of 18 and 25 years participated and were given £10 as an honorarium.

Stimuli, Design, and Procedure

Stimuli were the same as in Experiment 4. Six shapes (circle, plus, right triangle, horseshoe, diamond, parallelogram) were combined with any six of twelve colours (cyan, yellow, magenta, red, green, blue, brown, dark green, dark blue, violet, white, and pink) to form the stimuli. These were presented in six fixed locations in an invisible 3×4 grid of squares.

The experiment was designed as a 2×6 factorial experiment with repeated measures on both factors. The first independent variable was colours manipulated at two levels: unchanged colours vs. randomized colours. In the unchanged colours condition, all six colours remained the same from study to test display. In the randomized colours condition six colours were randomly chosen (with replacement) from the set of twelve colours and reallocated to different stimuli from study to test. Participants were asked to ignore the colours and to remember the combinations of shape and location, and the task was to detect whether the location-shape binding had changed. They were tested on two consecutive days at the same time of the day, half being tested with randomized colours, and the other half being tested with unchanged colours on the first day. There were 15 blocks of 24 trials in each experimental session. The six levels of the second independent variable (study-test interval) – 0, 500, 1000, 1500, 2000, and 2500 ms, were randomly presented within each block of 24 trials. A brief rest pause was enforced after every five blocks. In each session, participants practiced six trials of each type of study-test intervals, starting from the longest study-test interval, and working through all to the shortest one of 0 ms, and then finished off with a block of 12 trials in which the six study-test intervals were given in a random order (as in the real experiment). Thus they had 48 practice trials in total in each session, exactly the same as in Experiment 4. All other procedural details were the same as in Experiment 4.

Results

Mean change detection accuracy across study-test intervals for unchanged colours and randomized colours conditions are shown in Figure 6.7.

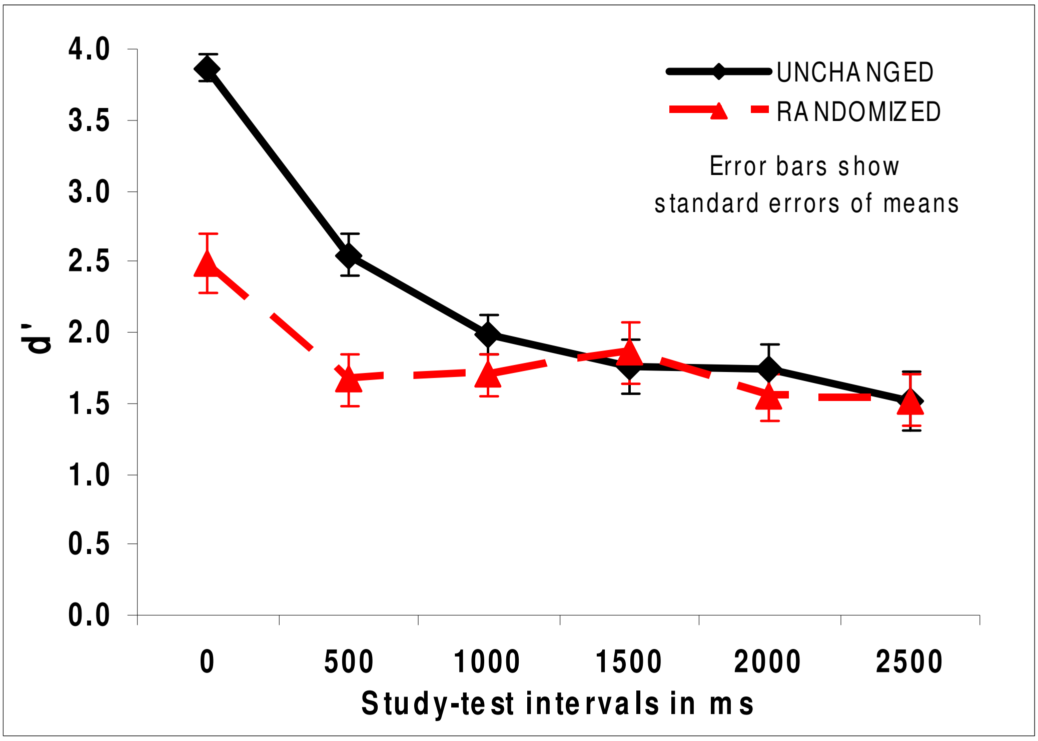
There was a significant main effect of colour condition $F(1,11)=15.504$, $MSE=.446$, $p<.002$, *partial* $\eta^2=.585$, in that memory for bindings was significantly reduced when the colour of stimuli was randomized from study to test display. The main effect of study-test interval was also significant, $F(5,55)=36.515$, $MSE=.240$, $p<.001$, *partial* $\eta^2=.768$ indicating that memory for bindings was significantly different for different study-test intervals. There was a significant interaction between these variables, $F(5,55)=14.491$, $MSE=.126$, $p<.001$, *partial* $\eta^2=.568$.

Planned comparisons with paired samples t test with Bonferroni adjustment showed that differences between the means for the unchanged and the randomized condition were reliable at 0 ms, $t(11)=6.939$, $p<.001$ and 500 ms, $t(11)=4.643$, $p<.001$ but not thereafter.

Despite the significant interaction effect, there is a decrease in performance as the study-test interval increases when colour remains unchanged as well as when the colour of stimuli is randomized from initial to test display.

Figure 6.7

Mean performance for unchanged and randomized colours for each study-test interval in Experiment 7



Single degree of freedom polynomial tests for unchanged colours showed negative slope linear trend, *F*(1,11)=137.514, *MSE*=.258, *p*<.001, *partial* η^2=.926, quadratic trend, *F*(1,11)=47.001, *MSE*=.179 , *p*<.001, *partial* η^2=.810, and cubic trend, *F*(1,11)=13.679, *MSE*=.136, *p*<.004, *partial* η^2=.554. For randomized colours, single degree of freedom polynomial tests also showed a negative slope trend. The linear, *F*(1,11)=21.215, *MSE*=.210, *p*<.001, *partial* η^2=.659, cubic, *F*(1,11)=17.372, *MSE*=.083, *p*<.002, *partial* η^2=.612, and quartic, *F*(1,11)=10.409, *MSE*=.092, *p*<.008, *partial* η^2=.486, trends were significant.

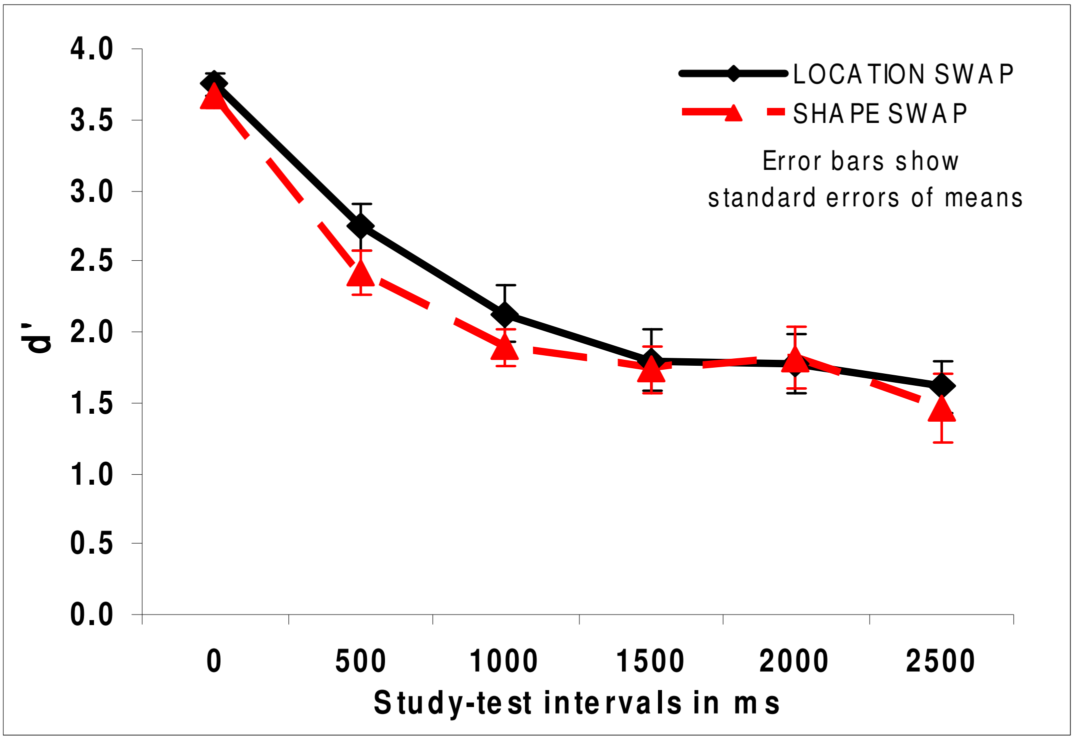
The fact that the higher order trends were also significant indicates that a linear trend does not fit the data too well, and both slopes are characterised by an initial decline followed by a levelling out. However, in both cases, the slope is negative. This is in contrast to the location and shape experiments, where performance improved with increasing study-test intervals when each feature was randomized.

Comparing swaps

Analyses for swaps in the randomized colours condition did not reveal any significant effects. However, in the unchanged colours condition, there was a significant main effect of swaps, $F(1,11)=6.669$, $MSE=0.101$, $p<.025$, *partial* $\eta^2=.377$, overall, location swaps being detected more often than shape swaps. The interaction effect was not significant. Figure 6.8 depicts the result.

Figure 6.8

Mean performance for location swaps and shape swaps with unchanged shapes for each study-test interval in Experiment 7



Planned comparisons at the various study-test intervals using paired samples directional t tests with Bonferroni adjustment showed no significant differences. Without Bonferroni adjustment, the significant difference was at 500 ms, $t(11)=2.256$, $p<.022$, favouring location swaps. Separate single degree of freedom polynomial tests for each kind of swap showed similar trends for both kinds of swaps with negative slopes. For shape swaps, linear $F(1,11)=64.297$, $MSE=0.449$, $p<.001$, *partial* $\eta^2=.854$, quadratic, $F(1,11)=55.539$, $MSE=0.122$, $p<.001$, *partial* $\eta^2=.835$, and cubic, $F(1,11)=9.134$, $MSE=0.273$, $p<.012$, *partial* $\eta^2=.454$, trends were significant. Similarly, for location swaps too, linear $F(1,11)=155.472$, $MSE=0.214$, $p<.001$, *partial* $\eta^2=.934$, and quadratic, $F(1,11)=19.016$, $MSE=0.329$, $p<.001$, *partial* $\eta^2=.634$, trends were significant.

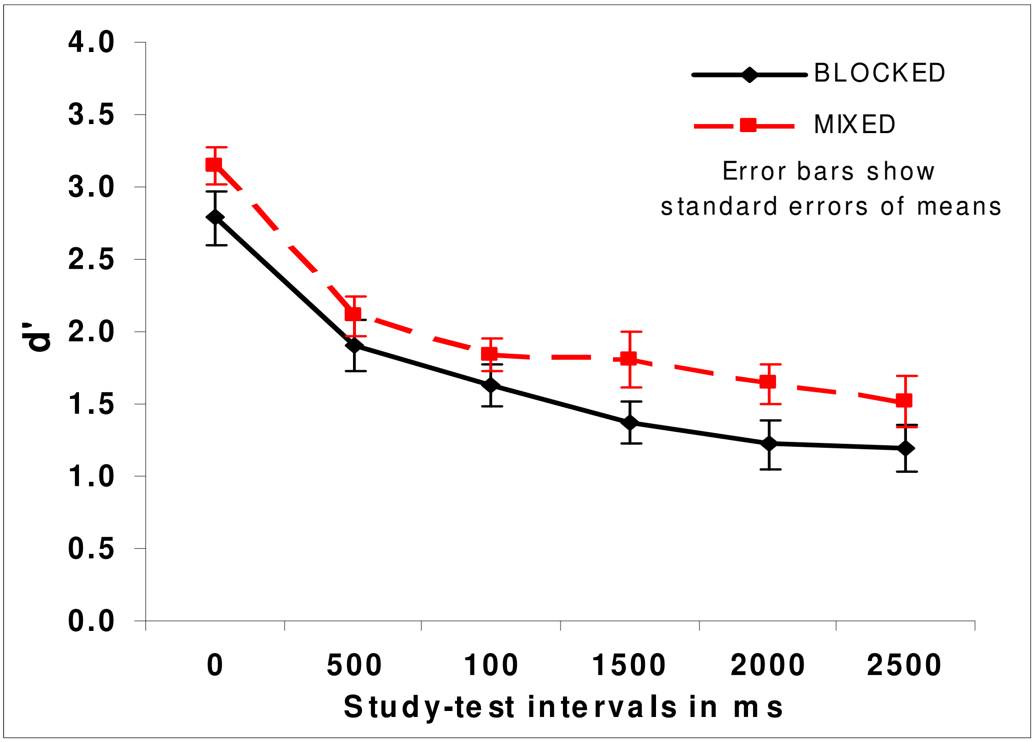
Comparing Experiments 7 and 4

A 2×2×6 ANOVA with experiments (between subjects), unchanged/randomized conditions (repeated measures), and study-test intervals (repeated measures) was carried out to compare Experiments 7 and 4. The main effect for experiments was not significant, though there was a trend towards significance $F(1,22)=3.245$, $MSE=2.350$, $p<.085$, *partial* $\eta^2=.129$. None of the interactions involving experiments were significant. Planned comparisons at the various study-test intervals using paired samples directional t tests with Bonferroni adjustment showed no significant differences. Without Bonferroni adjustment, the significant difference was at 1500 ms, $t(11)=1.803$, $p<.043$, and 2000 ms, $t(11)=1.969$, $p<.031$, in both cases favouring mixed presentation. Figure 6.9 shows how mixed presentation in Experiment 7 increased performance at all study-test intervals.

Separate single degree of freedom polynomial tests showed similar trends with negative slopes. For blocked presentation, linear $F(1,11)=52.724$, $MSE=0.353$, $p<.001$, *partial* $\eta^2=.827$, and quadratic, $F(1,11)=39.534$, $MSE=0.089$, $p<.001$, *partial* $\eta^2=.782$, trends were significant. Similarly, for mixed presentation, linear $F(1,11)=91.437$, $MSE=0.178$, $p<.001$, *partial* $\eta^2=.893$, quadratic, $F(1,11)=37.931$, *MSE*=0.099, *p*<.001, *partial* η^2=.775, and cubic, *F*(1,11)=24.783, *MSE*=0.066, *p*<.001, *partial* η^2=.693, trends were significant.

Figure 6.9

Mean performance for each study-test interval
with blocked (Experiment 4) and mixed (Experiment 7) presentation



Discussion

This experiment too replicated the interaction obtained in the previous experiments showing that the effects of the irrelevant feature were gradually removed and the bindings between the relevant features strengthened over time. Randomizing colours is disruptive of performance at 0 ms and 500 ms though the extent of disruption is not as much as that obtained in earlier experiments randomizing locations or shapes. The analyses comparing location swaps and shape swaps provide supportive evidence that it is easier to detect changes in locations than in shapes, affirming the importance of location as a feature.

Comparison with Experiment 4 clearly showed that mixed presentation helped performance at all study-test intervals in this experiment. The divergence is more clear at the study-test intervals of 1500 and 2000 ms. It appears that the more intensive use of WM resources entailed by mixed presentation has helped performance in the simple task of detecting changes to shape-location bindings, whilst the colour of the object changes.

COMPARING EXPERIMENTS 5, 6, AND 7

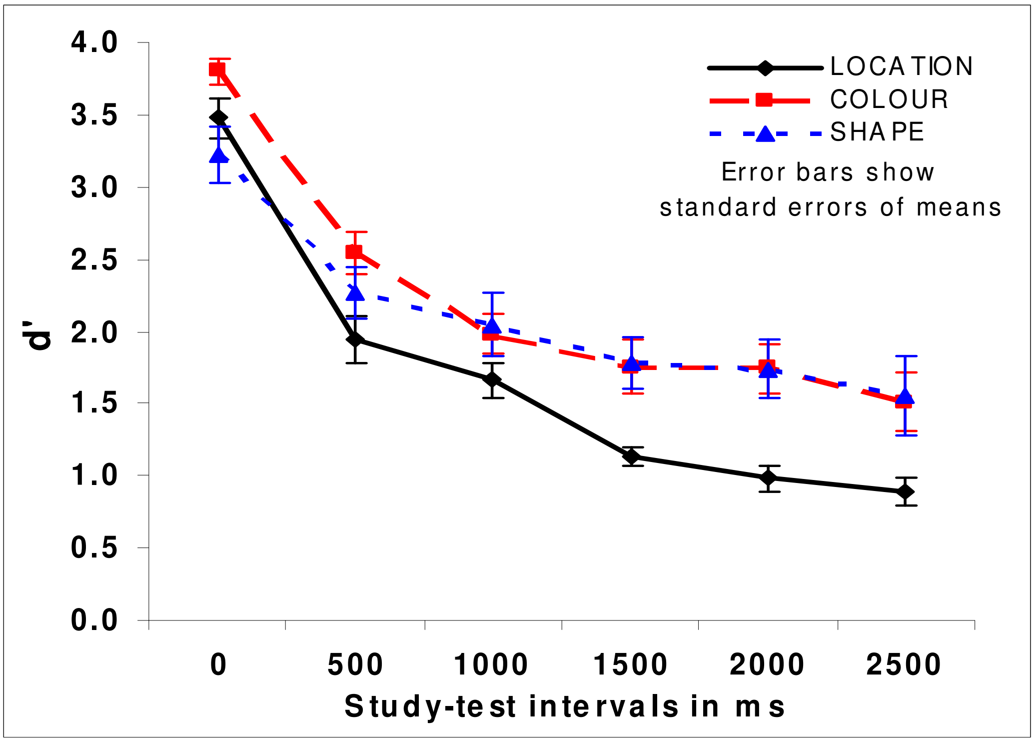
A 3×2×6 ANOVA with features (between subjects), unchanged/randomized conditions (repeated measures), and study-test intervals (repeated measures) was carried out to compare Experiments 5, 6, and 7. There was a significant three way interaction, $F(10,165)=4.622$, $MSE=0.158$, $p<.001$, *partial* $\eta^2=.219$, and significant two way interactions between unchanged/randomized conditions and features, $F(2,33)=3.750$, $MSE=0.610$, $p<.034$, *partial* $\eta^2=.185$, between study-test intervals and features, $F(10,165)=7.132$, $MSE=0.200$, $p<.001$, *partial* $\eta^2=.302$, and between unchanged/randomized conditions and study-test intervals, $F(3.633,119.881)=8.270$, $MSE=0.217$, $p<.001$, *partial* $\eta^2=.728$, with Greenhouse-Geisser correction applied. The main effects were significant for unchanged/ randomized conditions, $F(1,33)=62.499$, $MSE=0.610$, $p<.001$, *partial* $\eta^2=.654$, and study-test intervals, $F(3.641,120.144)=52.279$, $MSE=0.275$, $p<.001$, *partial* $\eta^2=.613$, with Greenhouse-Geisser correction applied, and features, $F(2,33)=11.271$, $MSE=2.195$, $p<.001$, *partial* $\eta^2=.406$.

To investigate the three-way interaction further, two way ANOVAs were conducted separately under unchanged and randomized conditions.

The 3×6 ANOVA for the unchanged condition with features as between subjects variable and study-test intervals as within subjects variable revealed a significant main effect for features, $F(2,33)=5.093$, $MSE=1.185$, $p<.012$, *partial* $\eta^2=.236$. Pairwise comparisons with Bonferroni adjustment showed a significant difference in the overall performance only between unchanged locations and shapes, with performance being significantly lower for locations. The main effect for study-test intervals was also significant, *F*(3.952,130.410)= 125.184, *MSE*=0.245, *p*<.001, *partial* η^2=.791, with Greenhouse-Geisser correction applied. There was also a significant interaction, *F*(10,165)=2.645, *MSE*=0.193, *p*<.005, *partial* η^2=.138. Figure 6.10 shows these results.

Figure 6.10

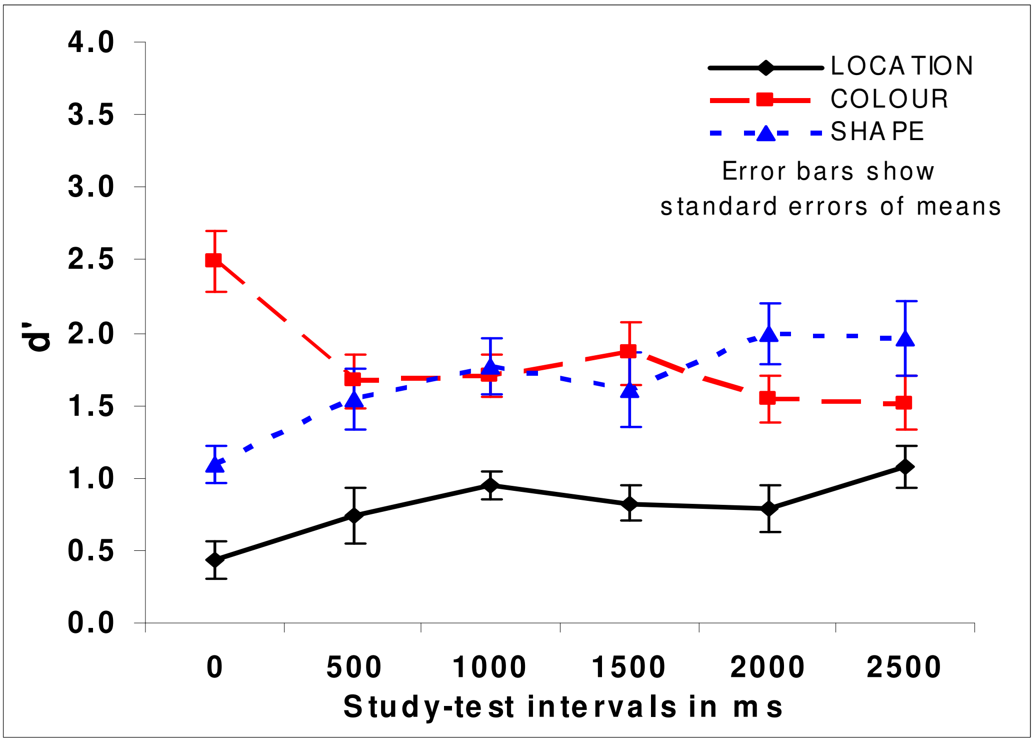
Mean performance for unchanged features for each study-test interval in Experiments 5, 6, and 7



The interaction was further explored by using single degree of freedom polynomial tests conducted separately for each feature. Negative slope linear, *F*(1,11)=245.114, *MSE*=.191, *p*<.001, *partial* η^2=.957, quadratic, *F*(1,11)=68.704, *MSE*=.129, *p*<.001, *partial* η^2=.862, and cubic, *F*(1,11)=7.809, *MSE*=.159, *p*<.017, *partial* η^2=.415, trends were found for locations. For shapes, reliable negative slope linear, *F*(1,11)= 40.991, *MSE*=.437, *p*<.001, *partial* η^2=.788, and quadratic, *F*(1,11)= 17.828, *MSE*=.163, *p*<.001, *partial* η^2=.618, trends were obtained. For colours, reliable negative slope linear, *F*(1,11)=137.514, *MSE*=.258, *p*<.001, *partial* η^2=.926, quadratic, *F*(1,11)=47.001, *MSE*=.179, *p*<.001, *partial* η^2=.810, and cubic, *F*(1,11)=13.679, *MSE*=.136, *p*<.004, *partial* η^2=.554, trends were obtained. Figure 6.10 clarifies that though the slope for all three features is negative, the interaction is primarily driven by the differences in the rate of decrease in performance over the different study-test intervals, and the significantly lower performance for locations at the longer study-test intervals.

The 3×6 ANOVA for the randomized condition with features as between subjects variable and study-test intervals as within subjects variable revealed results shown in Figure 6.11.

Figure 6.11
Mean performance for randomized features
for each study-test interval in Experiments 5, 6, and 7



There was a significant main effect for feature, *F*(2,33)=12.961, *MSE*=1.620, *p*<.001, *partial* η^2=.440. Pairwise comparisons with Bonferroni correction showed significantly lower performance when locations were randomized as compared to shapes as well as colours, with no significant difference between shapes and colours. The main effect for study-test intervals was not significant, but there was a significant interaction between the two variables, $F(10,165)=9.985$, $MSE=0.165$, $p<.001$, *partial* $\eta^2=.377$.

The interaction was further investigated using separate single degree of freedom polynomial tests for each feature. For randomized locations, single degree of freedom polynomial tests showed a reliable positive slope linear trend, $F(1,11)=17.800$, $MSE=.102$, $p<.001$, *partial* $\eta^2=.618$, and cubic trend, $F(1,11)=8.726$, $MSE=.089$, $p<.013$, *partial* $\eta^2=.442$. For randomized shapes, only the linear trend, $F(1,11)= 17.848$, $MSE=.298$, $p<.001$, *partial* $\eta^2=.619$, was significant, and it had a positive slope. For randomized colours, single degree of freedom polynomial tests shows a reliable negative slope linear trend, $F(1,11)=21.215$, $MSE=.210$, $p<.001$, *partial* $\eta^2=.659$, cubic trend, $F(1,11)=17.372$, $MSE=.083$, $p<.002$, *partial* $\eta^2=.612$, and quartic trend, $F(1,11)=10.409$, $MSE=.092$, $p<.008$, *partial* $\eta^2=.486$.

GENERAL DISCUSSION

Experiments 5, 6, and 7 tested the participants' ability to ignore changes in location, shape, and colour, with the study-test intervals randomly mixed in each block. This was in contrast with Experiments 2, 3, and 4, which used blocked presentation. In line with the expectation based on previous work on the contextual interference effect (Lee & Magill, 1985; Li & Wright, 2000; Shea & Zimny, 1988; Wright et al., 1992), mixed presentation did result in better performance at longer study-test intervals in the experiments where shapes were to be ignored, and at all study-test intervals when colours were to be ignored. However, when locations were to be ignored, there was an interaction with blocked presentation resulting in better performance at 2000 ms.

This contrary result regarding locations might have occurred because detection of colour-shape bindings whilst locations are to be ignored is a more complex task than detecting bindings of shape or colour to locations. As reviewed by Wulf and Shea (2002) the contextual interference effect is not obtained for complex tasks. The result is also understandable if the different kinds of attention that are operational in these experiments are considered. In the experiments where location is to be ignored, attention needs to be either object based or based on the features of colour and shape; it cannot be location based. Essentially these experiments explore the role of locations in object-based attention. There is an attentional set to focus on the features of the objects, which is aided by blocked presentation. The effect is most clear at 2000 ms after the features have been selectively bound and irrelevant locations have been deleted from the object representation. Object or feature based attention, operates subsequent to the identification of stimuli. By definition, it is tied to the stimuli in the visual field, and thus benefits from the narrow focus on features of the stimuli in each trial that is dictated by blocked presentation. This conjecture is supported by evidence that the object facilitates the guidance of attention to a target object only when location information is unavailable (Moore & Egeth, 1998, Shih & Sperling, 1996).

However, in Experiments 3/6 and 4/7 where the stimuli were presented in the same six locations in every trial and every presentation, attention is location based as well as object and feature focussed. The question being addressed in these experiments is regarding the relevance of shapes and colours in the context of spatial attention. Physiological evidence regarding processing of locations and objects in different streams supports theoretical notions that spatial attention is different from object or feature based attention (Treisman, 2006; Velichkovsky, 2007), and empirical studies that locations are attended to before objects or their features (Becker & Rasmussen, 2008; Shomstein & Behrmann, 2008). Spatial attention is not contingent on the presence of specific stimuli in the visual field. In the extent of its focus, it operates more like a global set or expectancy for the occurrence of the stimuli. In a way, it provides the context for object-based attention to operate. Mixed presentation favours this type of attention, because it utilizes generalized expectancies rather than only task focussed ones.

There is certainly a greater use of WM resources in the mixed condition. Resources are required for both inter-trial and intra-trial processing. Switching task set from one trial to another is resource demanding, and participants cannot settle into performing each trial the same way. As soon as the expectancy of the test stimuli occurring at short study-test interval is disconfirmed, mental rehearsal might be used to maintain the spatial configuration of stimuli. This intensive use of WM resources leads to better performance with mixed presentation, especially at longer study-test intervals in line with the contextual interference effect. In all these analyses, the unchanged/ randomized variable was neither significant as a main effect, nor did it interact with any of the other effects.

With regard to the driving question of these experiments, whether and how top-down processes dictated by task relevance of features overcome the basic fast-feed forward processing differences among features, the results echoed the pattern of results, i.e., the interaction obtained in Experiments 2, 3, and 4. The results of each experiment show that the differences in the three experiments are largely driven by the disruption of performance at the shorter study-test intervals, and the differences in the time taken to overcome this disruption.

Taken together, the significant interaction observed in experiments 1-7 shows that the randomization of the ‘to be ignored’ features affects performance negatively immediately after the stimulus is presented. However, after some time, it is possible to overcome this disruption, and performance is not significantly different from when the feature remains unchanged. Thus a process of selection does operate, whereby relevant features are consolidated, and irrelevant features are suppressed or inhibited. This process however, is not immediate and takes some time. Presumably, all features are initially bundled together, and gradually a process of selection refines the representation, eventually to comprise only the binding of relevant features.

The experiments also suggest that different features are processed at different rates, because the time it takes for the visual system to recover from the disruption varies with individual features. As compared to shape and colour, randomising location is most disruptive of performance, and consequently, the visual system takes the maximum time to inhibit changes in location, and the differences between unchanged and random location cease to be significant only around 1500 ms. Shape appears to be the next in importance, the disruption caused by its randomization being almost half of the disruption caused by the randomization of locations. The visual system takes only about 1000 ms to overcome this disruption. Out of the three features tested here, colour seems to be least important, the disruption caused by randomized colours being the least, and the graph line for randomized colours largely follows the one for unchanged colours. Yet randomising colour does disrupt performance to some extent, which is overcome at 1000 ms. Thus, the gradual process of selection of relevant features and inhibition of irrelevant features follows a different time course for each kind of binding. Additional analyses of swaps support these differences, as they show that location swaps are more easily detected as compared with shape swaps and colours swaps.

Nevertheless, Experiments 1-7 all show that it is possible to ignore irrelevant features, however strong they may be initially. There is a gradual process of selection, whereby relevant features are selected for binding and irrelevant ones are inhibited, which leads to well-defined objects, which lend themselves to further processing.

CHAPTER 7

EXPERIMENTS 8, 9, AND 10

The experiments described in this and the next chapter were conducted only for the feature of locations. Although differences in the rates of processing among the three features were noted in the previous experiments, the effect of top-down inhibitory process acting on these features was similar. Specifically, when irrelevant, the feature had an initial effect that was, nevertheless, no longer present at the longer study-test intervals. In this sense, location was not special. In addition, the disruptive effect was clearest for experiments in which location was the irrelevant feature, and the role of the factors explored in further experiments was most likely to be displayed in a significant manner in experiments involving locations.

The motivation for the experiments delineated in this chapter was to distinguish further between bottom-up and top-down factors in the process of binding by using a backward mask. An immediate mask was used to interfere with percept driven iconic memory, and a delayed mask to interfere with the central, cognitive processes of consolidation and inhibition at 300 ms after stimulus offset. This follows earlier literature reviewed in Chapter 2, which has shown differential effects of masks when presented immediately after the target presentation or after a delay, presumably because an immediate mask interrupts peripheral, perceptual, lower level processes, whereas a delayed mask interrupts central, conceptual, higher level cognitive processes (Bongartz & Scheerer, 1976; Jacewitz & Lehmann, 1972; Loftus & Ginn, 1984; Potter, 1976; Turvey, 1973). A recent study by Sligte et al. (2008) used an energy mask (a non-informational flash of light) to disrupt iconic storage, and a pattern mask to disrupt VSTM. Based on differences in performance due to these two masks, they proposed three stages in visual information processing (a) an iconic memory disrupted by a flash of light, (b) a long lasting but fragile VSTM with a larger capacity than (c) a robust VSTM with a capacity of four items. Their conclusions about these three stages in processing as well as the previous literature on the perceptual-conceptual distinction in processing, suggest that the timing of the mask is more important than its type. But, as discussed in Chapter 2, in most previous studies, the kind of mask and the timing of the mask are confounded. Thus a single type of mask was used in the present experiments, either immediately or after a delay, so that any differences in performance could be attributed only to the effect of the timing of the mask.

In Experiment 9, the mask was presented immediately after the study display. The traditional view of masking suggests that the mask would completely wipe out the contents of iconic memory (e.g., Becker et al., 2000; Neisser, 1967; Sperling, 1960, 1963). If it is assumed that performance is driven by iconic memory alone, then it would be predicted that there would be no difference between the unchanged and randomized locations conditions in Experiment 9 for there would be no remnants of the study display to be matched with the test display in the unchanged location condition or mismatched with the test display in the randomized location condition. Iconic storage being automatic and the order of presentation of the trials being mixed in these experiments, participants would not know whether the test display would match or mismatch the study display and thus would not be able to use differential strategies to encode items during the study display in the randomized and unchanged location conditions. Indeed, if taken to an extreme, the view that the mask terminates the icon would suggest performance at chance levels in both cases.

Nevertheless, theoretical and empirical evidence regarding persistence of information suggests that the mask does not erase all information. Not only is there a transfer of information into a durable storage or VSTM before the mask appears (Averbach & Coriell, 1961; Gegenfurtner & Sperling, 1993) there are active ongoing processes that act on the contents of the icon to transform them into meaningful bits of information (Erwin, 1976). In the present experiments, the participant knows in advance that location is irrelevant and can try to delete it from the representation and remember only the relevant features right from the outset. However, as shown by previous experiments, this selective process is not immediate and takes time. As far as location is inevitably a part of the stimulus representations in VSTM, which survive the mask, performance would differ in the unchanged and randomized location conditions in Experiment 9. In the randomized locations condition performance would be disrupted because there would be a mismatch between the contents of VSTM and the test display. In the unchanged condition, the test display would match the preserved contents in VSTM making the swap easier to discern. Nonetheless, the effects of retinotopic iconic memory would be removed from the performance of the participant. It also seems that in previous Experiments 2 and 5, it is the performance in the unchanged location condition at shorter study-test intervals, which benefits from the iconic memory of the study display. So the immediate mask might be expected to have a greater effect in the unchanged locations condition than in the randomized locations condition, particularly at the short study-test intervals.

In Experiment 10, the mask was presented after a delay. Masks presented after various delays have been often used to study higher processes such as categorization and grouping (Kurylo, 1997), selective attention (Di Lollo et al., 2000), consolidation in VWM (Vogel et al., 2006), and to assess whether the encoding of VWM representations is an all or none process (Zhang & Luck, 2008). In the present study, a delayed mask was used to interrupt the central, top-down process, which presumably leads to selective consolidation of relevant features and inhibition of irrelevant features, which was evident in the experiments detailed in the previous chapter.

If it were assumed that differential performance at the shorter study-test intervals in the earlier experiments is driven by iconic memory alone, then performance in Experiment 10 would be lower than that in Experiment 9, for the mask would interrupt a decayed icon. On the other hand, the assumption might be that the mask interrupts the process of transfer of information from the icon to VSTM, an assumption made by all researchers using masks to study consolidation into VSTM (e.g., Vogel et al., 2006). Since the delayed presentation of the mask allows a greater amount of information to be transferred into VSTM, performance levels would be higher than those in the Experiment 9, otherwise the differences between unchanged and randomized condition remain and would reflect the ones found in Experiment 9.

Even this view, however, is limited, for it assumes that participants' performance reflects only the process of consolidation or non-selective transfer of objects from the study display and its iconic memory to VSTM; it assumes that the flow of information is only feed-forward.

If the mask can interfere with the process of consolidation, it is plausible that it also interrupts the top-down process of inhibition. There seems to be no direct evidence in literature of a mask being used to interrupt the process of inhibition. However, using the preview search paradigm, Watson and Humphreys (2005) have shown that if another set of related distracters is introduced in the preview period, the preview benefit is reduced. Also, blinking a set of distracters on and off in the beginning of the preview period disrupts performance, whether or not the distracters are related to the target. The former probably is due to central masking after a delay, while the blinking distracters would be similar to an energy mask and have a peripheral or perceptual masking effect. In this context, it is important to note the similarity between the preview search paradigm devised by Watson and Humphreys (1997) and the present experimental task. In both cases, the participants are shown two displays one after the other. They encode and maintain a representation of the first display in memory, and search for the 'target' among distracters in the second display. The difference essentially lies in how the target is defined. In preview search, the target is not present in the preview, but it is pre-defined by the experimenter. In the present experiments, the participant focuses on a few stimuli, the task being beyond VWM capacity anyway, and thus self selects the targets to be remembered.

Many recent studies have shown that a mask interrupts top-down recurrent activity, not only with four dot masking (Di Lollo et al., 2000), but also when a pattern mask is used (Enns & Oriet, 2007; Fahrenfort et al., 2007). The top-down process of attentional control, which inhibits irrelevant information, is theoretically and empirically, well established by studies of attentional blink and preview benefit reviewed in Chapter 2. Further, EEG studies by Luck and his co-workers, and Jolicoeur and his associates, clearly show that inhibition lags behind consolidation in temporal sequence. Logically, there has to be something to inhibit before the process begins! There is also ample empirical evidence that the process of active inhibition is especially dominant around 300 ms after offset or 500 ms after onset of the stimulus (Braithwaite et al., 2007; Chun & Potter, 1995; Humphreys et al., 2004; Maruff et al., 1999; Watson & Humphreys, 1997, 2000, 2002). This is substantiated by physiological evidence as well (Edin et al., 2007).

As per the discussion of results in previous chapters, the performance of participants manifests inhibition in the randomized locations condition. If the mask interrupts this process of inhibition, the performance of the participants would show a rebound at the initial test, and would manifest whatever has been selectively consolidated in VSTM at that point. Thereafter, the trend for the randomized and unchanged conditions would be similar in that both would reflect forgetting from the VSTM.

Such a rebound is not expected in the unchanged locations condition, because performance in this condition anyway does not manifest the inhibitory effect. Based on their studies of visual marking, Watson and Humphreys (1997) proposed that inhibition is used only if required. This also fits with research showing that WM can be strategically used to facilitate or inhibit the process of attentional selection (Woodman & Luck, 2007). This specific prediction that the delayed mask will have a greater effect on performance as compared with performance with no mask or an immediate mask in the randomized locations condition will be tested with planned comparisons of performance at the initial study-test interval in the randomized locations condition for all the three experiments.

Analogously, the specific prediction that an immediate mask would have a greater effect on performance as compared with performance with no mask or a delayed mask in the unchanged condition will be tested with planned comparisons of performance at the initial study-test interval in the unchanged locations condition for all three experiments. This prediction is made based on the assumption that iconic memory has a greater role to play in the unchanged locations condition, but its effects persist only for a limited period. Studies by Phillips (1974) and Loftus et al. (1982) and Loftus et al. (1995) extensively reviewed in Chapter 2, suggest that the icon does not persist beyond the initial 100 ms or so with a display duration of 200 ms. Thus, the delayed mask given at 300 ms after stimulus offset is not likely to have an effect on iconic memory.

Thus, three experiments were designed together. Experiment 8 provided the baseline for the masking experiments. Experiment 9 studied the effect of an immediate mask, whereas Experiment 10 studied the effect of a delayed mask.

EXPERIMENT 8

Experiment 8 was carried out to provide a baseline to compare with the masking experiments. It was essentially a replication of Experiments 1, 2, and 5, but with the important difference that all levels of both factors were randomly mixed and then presented to the participant. The effect of mixing study-test intervals was tested in the experiments reported in Chapter 6. Experiment 8 mixed unchanged and randomized conditions as well. Mixed presentation of conditions compels participants to adopt strategies that allow them to prepare for all different task possibilities (Kleinsorge, Heuer, & Schmidtke, 2004; Slagter et al., 2006). Thus Experiment 8 tested whether the difference in participants' performance in unchanged and randomized conditions could be due to the use of different strategies, as these conditions were administered in different blocks, and indeed on different days in earlier experiments. If the difference in the participants' performance in the unchanged and randomized conditions at the shorter study-test intervals observed in earlier experiments occurred due to different strategies being used by the participants, then that difference was expected to be significantly reduced in this experiment, for mixed presentation precludes differential strategies. If the results obtained are similar to Experiments 2 and 5, it would strengthen the idea that difference in performance at the shorter study-test intervals and similar performance at longer study-test intervals in the previous experiments is probably not due to differential strategies deliberately adopted by the participants in unchanged and randomized locations conditions; rather it indicates the gradual impact of top-down processes to ignore the irrelevant feature.

In keeping with the contextual interference effect, it is also possible that performance in the longer study-test intervals shows an upsurge in both the unchanged and randomized conditions. The contextual interference effect is the observation that mixed random presentation of experimental conditions results in poorer performance if tested immediately, but in superior performance when memory is tested after a gap of time (reviewed by Magill & Hall, 1990). It is suggested that this is due to greater use of WM resources as the participants shift from one kind of task to another (Lee & Magill, 1985) and need to use extra resources for intra-task as well as inter-task processing (Shea & Zimny, 1988; Wright et al., 1992). Performance did not show the contextual interference effect for the locations experiments among the experiments reported in the Chapter 6. However, Experiment 5 only mixed the presentation of study-test intervals, where the participant merely needs to wait passively for the test display to occur in the different conditions. In contrast, Experiment 8 involved mixed presentation of unchanged and randomized conditions as well. Thus it is expected that mixed presentation might boost performance at the longer than the shorter study-test intervals in both the unchanged and randomized locations conditions in keeping with the contextual interference effect.

Participants

Twelve students (6 men and 6 women) in the age range 18-25 years were given an honorarium of £10 for their participation in the experiment.

Stimuli, Design and Procedure

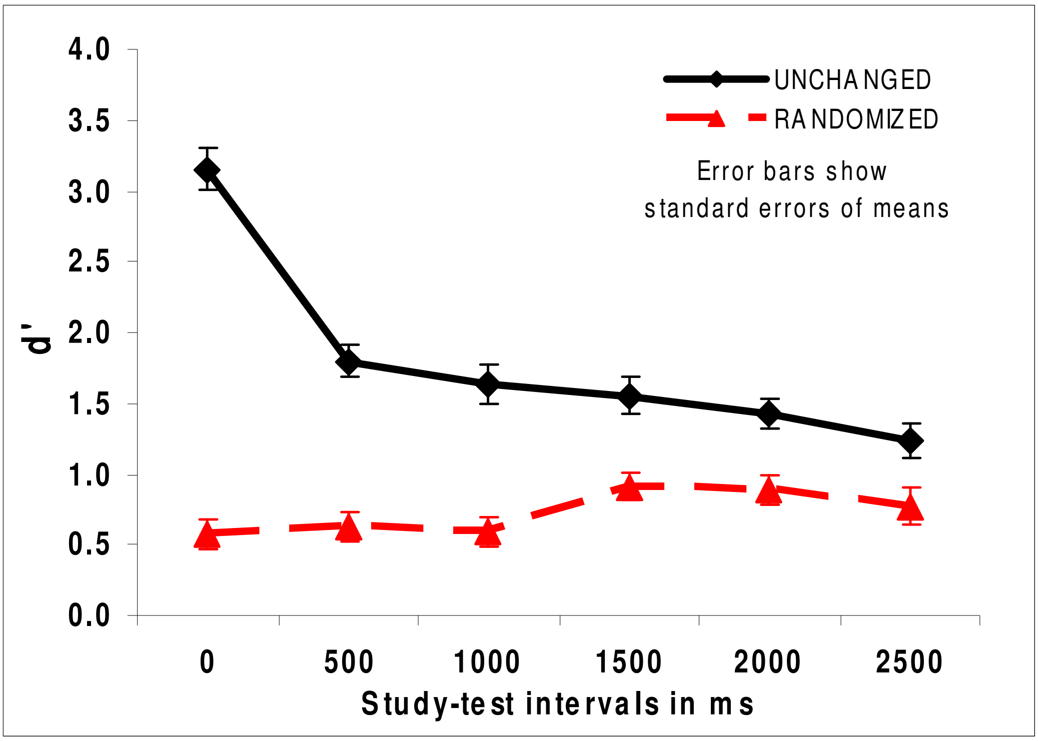
These were identical to Experiment 1, 2, and 5 except that the experiment was completed in a single session with reduced total number of trials, and all the conditions of the experiment were randomly mixed within each block. Thus, within each block of trials, on half of the trials, stimuli were presented in unchanged locations, and on the other half they were presented in randomized locations, both types of trials randomly intermixed. The six study-test intervals were also presented in a random sequence within each block. To enable completion in a single session, the total number of trials was reduced and each participant completed 10 blocks of 48 trials in a single session, doing 480 trials in all.

Results

All statistical tables for this chapter appear in Appendix D. Mean swap detection performance calculated from d-primes across study-test intervals for the unchanged/randomized locations conditions is shown in Figure 7.1.

Figure 7.1

Mean performance for unchanged and randomized locations for each study-test interval in Experiment 8



A 2×6 ANOVA was carried out to analyze the results. A reliable main effect of unchanged/ randomized locations was observed, *F*(1,11)=208.196, *MSE*=0.199, $p<.001$, *partial* $\eta^2=.950$, showing that memory for bindings was reduced when locations of stimuli were randomized between study and test. The main effect of study-test intervals was also reliable, *F*(5,55)=14.021, *MSE*=0.160, $p<.001$, *partial* $\eta^2=.560$, indicating that memory for bindings varied across study-test intervals. As with Experiments 1, 2, and 5, these variables interacted, $F(5,55)=35.666$, $MSE=0.105$, $p<.001$, *partial* $\eta^2=.764$.

Planned comparisons using paired samples t test with Bonferroni adjustment showed that differences between the means for the unchanged and the randomized condition were reliable at all study-test intervals except the last one of 2500 ms, though the unadjusted t-ratio was significant for 2500 ms too, $t(11)=2.817$, $p<.017$. The exact figures for the other study-test intervals were, $t(11)=19.521$, $p<.001$, for 0 ms; $t(11)=9.644$, $p<.001$, for 500 ms; $t(11)=6.242$, $p<.001$, for 1000 ms; $t(11)=4.297$, $p<.001$, for 1500 ms; and $t(11)=5.133$, $p<.001$, for 2000 ms.

Separate single degree of freedom polynomial tests within each condition were also done. In the unchanged locations condition, performance across study-test intervals was characterized by reliable negative-slope linear $F(1,11)=99.034$, $MSE=.202$, $p<.001$, *partial* $\eta^2=.900$, quadratic, $F(1,11)=48.612$, $MSE=.105$, $p<.001$, *partial* $\eta^2=.815$, cubic, $F(1,11)=12.958$, $MSE=.230$, $p<.004$, *partial* $\eta^2=.541$, and quartic trends $F(1,11)=8.720$, $MSE=.058$, $p<.013$, *partial* $\eta^2=.442$. In contrast, for the randomized locations, performance was characterized by reliable positive-slope linear trend, $F(1,11)=5.547$, $MSE=.130$, $p<.038$, *partial* $\eta^2=.335$.

Comparing swaps

Additional analyses to test if colour swaps and shape swaps had a differential effect on the participants' performance, showed that in the randomized as well as unchanged locations conditions, neither the main effect of swaps, nor the interaction between swaps and study-test intervals was significant.

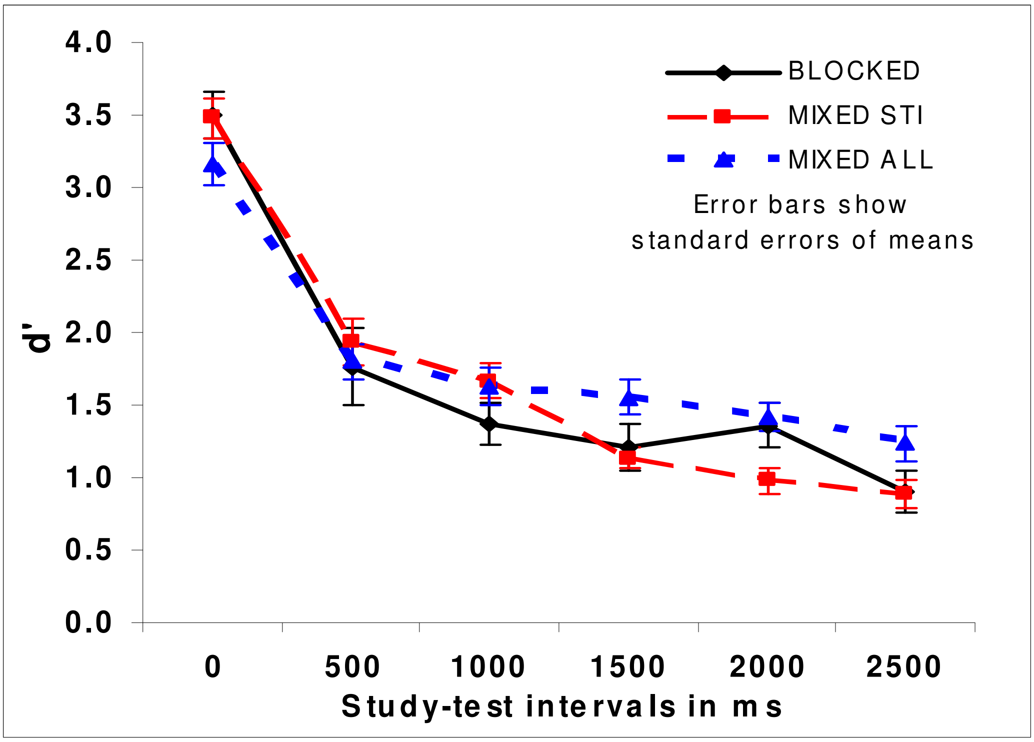
Comparing Experiment 8 with Experiments 2 and 5

A 3×2×6 ANOVA with experiments (between subjects), unchanged/randomized locations (repeated measures), and study-test intervals (repeated measures) was carried out to compare Experiments 2, 5, and 8. Though the main effect for experiments was not significant, there was a significant two way interaction between experiments and study-test intervals, $F(10,165)=2.886$, $MSE=.146$, $p<.002$, *partial* $\eta^2=.149$, and also a significant three way interaction, $F(10,165)=2.144$, $MSE=.155$, *p*<.024, *partial* η^2=.115. This indicated that the nature of interaction between study-test intervals and experiments differed under unchanged and randomized conditions.

To investigate the three-way interaction, two way ANOVAs were conducted separately under unchanged and randomized conditions. Figure 7.2 shows the results of the 3 ×6 ANOVA for unchanged locations with experiments as the between subjects variable and study-test intervals as the within subjects variable.

Figure 7.2

Mean performance for each study-test interval in Experiments 2, 5, and 8 for unchanged locations



As Figure 7.2 shows, in the unchanged locations condition, though the main effect of experiments was not significant, the interaction between experiments and study-test intervals was significant *F*(10,165)=2.930, *MSE*=0.175, *p*<.002, *partial* η^2=.151. As the graph clearly shows, performance at the shorter study-test intervals is similar, but diverges at the longer study-test intervals, with best results for mixed presentation of all conditions in Experiment 8. Single degree of freedom polynomial tests for the unchanged locations condition showed that in Experiment 2, with blocked presentation, performance across study-test intervals was characterized by reliable negative slope linear $F(1,11)=131.030$, $MSE=0.288$, $p<.001$, *partial* $\eta^2=.923$, quadratic, $F(1,11)=53.584$, $MSE=0.220$, $p<.001$, *partial* $\eta^2=.830$, and cubic trends, $F(1,11)=53.422$, $MSE=0.126$ $p<.001$, *partial* $\eta^2=.829$. In Experiment 5 with mixed presentation of study-test intervals, there was a reliable negative slope linear trend, $F(1,11)=245.114$, $MSE=0.191$, $p<.001$, *partial* $\eta^2=.957$, quadratic trend, $F(1,11)=68.704$, $MSE=0.129$, $p<.001$, *partial* $\eta^2=.862$, and cubic trend, $F(1,11)=7.809$, $MSE=0.159$, $p<.017$, *partial* $\eta^2=.415$. In Experiment 8, with mixed presentation of all conditions, performance was characterized by reliable negative slope linear $F(1,11)=99.034$, $MSE=0.202$, $p<.001$, *partial* $\eta^2=.900$, quadratic, $F(1,11)=48.612$, $MSE=0.105$, $p<.001$, *partial* $\eta^2=.815$, cubic, $F(1,11)=12.958$, $MSE=0.230$, $p<.004$, *partial* $\eta^2=.541$, and quartic $F(1,11)=8.720$, $MSE=0.058$, $p<.013$, *partial* $\eta^2=.442$, trends.

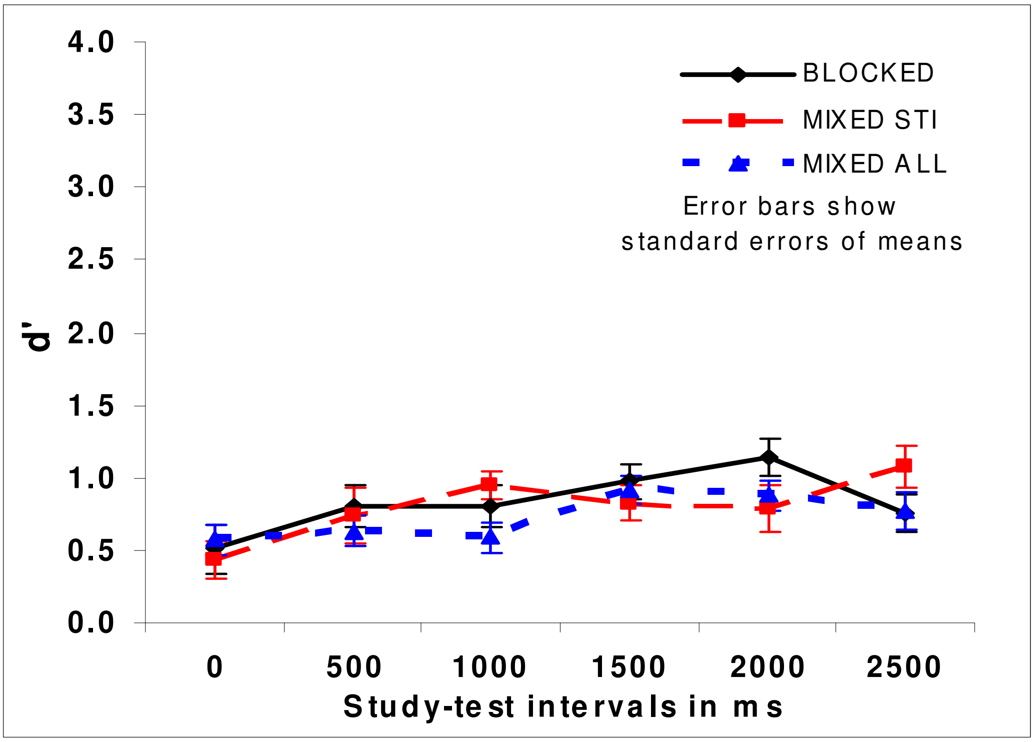
Figure 7.3 shows the results of the 3×6 ANOVA for randomized locations with experiments as the between subjects variable and study-test intervals as the within subjects variable. Again, the main effect for experiments was not significant, but there was a significant interaction, $F(10,165)=1.913$, $MSE=0.126$, $p<.047$, *partial* $\eta^2=.104$. As the graph shows, the performance in the three experiments varies inconsistently across the three experiments for the various study-test intervals, though the slope is positive in all cases.

Single degree of freedom polynomial tests for randomized locations showed that in Experiment 2, with blocked presentation, performance was characterized by reliable positive-slope quadratic trend, $F(1,11)=7.114$, $MSE=.156$, $p<.022$, *partial* $\eta^2=.393$. In Experiment 5, with mixed presentation of study-test intervals, performance showed a reliable positive slope linear trend, $F(1,11)=17.800$, $MSE=.102$, $p<.001$, *partial* $\eta^2=.618$, and cubic trend, $F(1,11)=8.726$, $MSE=.089$, $p<.013$, *partial* $\eta^2=.442$. In Experiment 8, with mixed presentation of all conditions, performance was characterized only by a reliable positive-slope linear trend, $F(1,11)=5.547$, $MSE=.130$, $p<.038$, *partial* $\eta^2=.335$.

Figure 7.3

Mean performance for each study-test interval

in Experiments 2, 5, and 8 for randomized locations



Discussion

Experiment 8 essentially replicated Experiment 1, 2, and 5, in showing that randomizing location between study and test was highly disruptive of detection of colour-shape bindings. This disruption gradually decreases and yields a significant interaction effect. The graph for this experiment does not show a convergence and differences between unchanged and randomized conditions are significant at all but the last study-test interval. This actually reflects the superior performance in Experiment 8 in the unchanged locations condition at the longer study-test intervals, as was manifest in the ANOVA comparing Experiments 2, 5, and 8.

This increase in detection at the longer study-test intervals and the non-significant but slight decrease at 0 ms follows the contextual interference effect. The question is why performance follows the contextual interference effect only in the unchanged locations condition and not in the randomized locations condition. In answer, it is important to consider how the participants might have approached this experiment. The participants do not know whether the trial is with the test display unchanged or randomized, or what is the study-test interval. Consequently, compelled to adopt strategies that ensure success in all conditions (Kleinsorge et al., 2004; Slagter et al., 2006) they prepare for and are set for the worst-case scenario of randomized condition. When the test display is indeed randomized as compared to the study display, they simply give their response. But, when the test display is unchanged, it requires a shift in task set, which uses additional WM resources and results in the contextual interference effect being manifest only in the unchanged locations condition. In a way, the occurrence of this pattern of results confirms that the participants followed the same strategy of focussing on the relevant features and deleting the irrelevant ones in both the unchanged and randomized experimental conditions.

It is noteworthy that at the shorter study-test intervals, levels of performance in the unchanged as well as randomized conditions are close to those obtained in Experiment 2 and 5, and overall, the results essentially replicate the results of Experiment 2 and 5. The experiment thus provides an adequate and sound baseline performance to compare with the masking experiments 9 and 10.

EXPERIMENT 9

Experiment 9 used a pattern mask to study the role of early stage percept driven iconic memory in the performance of the participants. The archetypal view suggests that masking immediately after or at short time delays after the target completely terminates the icon (Sperling, 1960, 1963; Neisser, 1967; Becker, et al., 2000). It is questionable though, how far a mask can affect performance based on iconic memory. A conceptualization of iconic memory as a non-selective, large capacity but short-term buffer is quite simplistic. There is little agreement even on its duration. An indication of further complexity comes from studies by Dick (1969) and

Townsend (1973) who found that errors in iconic memory were location errors rather than intrusion errors, suggesting that it is the location, rather than identity of objects, which deteriorates over time. Phillips (1974) distinguished between sensory storage and VSTM, showing that the former could be masked, whereas the latter was immune to a mask. Erwin (1976) demonstrated that the icon is not mere visible persistence of the stimulus, and post sensory processes relentlessly organize the information in iconic memory.

Some researchers specifically suggested that iconic storage can been distinguished as an early retinotopic buffer, followed by a spatiotopic representation of stimuli (Breitmeyer et al., 1982; Feldman, 1985; McRae et al., 1987). Analogous to these ideas, Coltheart (1980) affirmed that iconic memory is neither visible nor neural (retinal) persistence rather it is informational persistence. This was empirically confirmed by Loftus and Irwin (1998). In line with this assertion, Smithson and Mollon (2006) asked whether a mask can completely obliterate an icon. In their experiments, they presented a cue after a backward checkerboard pattern mask, which still allowed selection within a target array with a target-mask interval of 100 ms, though performance was at chance at 0 ms. They concluded that the mask cannot penetrate higher levels of visual analysis and representation of stimuli in terms of conceptual, abstract properties or categorical objects.

Therefore, it was of interest to explore how far the pattern mask used in the present experiment would disrupt iconic memory, and if it would affect performance differentially in unchanged and randomized locations at various study-test intervals. It was expected that the effect would be greater at shorter study-test intervals (until the icon persists). In line with abovementioned studies, which suggest that in the later stages, iconic memory is spatiotopic rather than retinotopic, it might be expected that the immediate pattern mask would have a greater effect on performance in unchanged locations condition. These spatiotopic representations can also be thought of as VSTM representations, the distinction between the two being more theoretical rather than empirical. Both are present at a stage subsequent to the initial retinotopic representations, and neither seems vulnerable to a mask.

Thus, as mentioned in the introduction of this chapter, to the extent that locations are a part of the stimulus representations that survive the mask, performance would differ in the unchanged and randomized location conditions in this experiment. The match between the surviving representations and the test display would make the swap easier to detect in the unchanged locations condition, but the mismatch in the randomized locations condition would make it more difficult.

Nevertheless, the effects of retinotopic iconic memory would be eradicated from the performance of the participant. Since performance in the unchanged location condition presumably benefits more from iconic memory of the study display than the randomized conditions in Experiment 8 (and also 2 and 5), the immediate mask would have a greater effect in the unchanged locations condition than in the randomized locations condition, particularly at the shorter study-test intervals.

Participants

Twelve students (6 men and 6 women) in the age range 18-25 years participated in the experiment and were given an honorarium of £10.

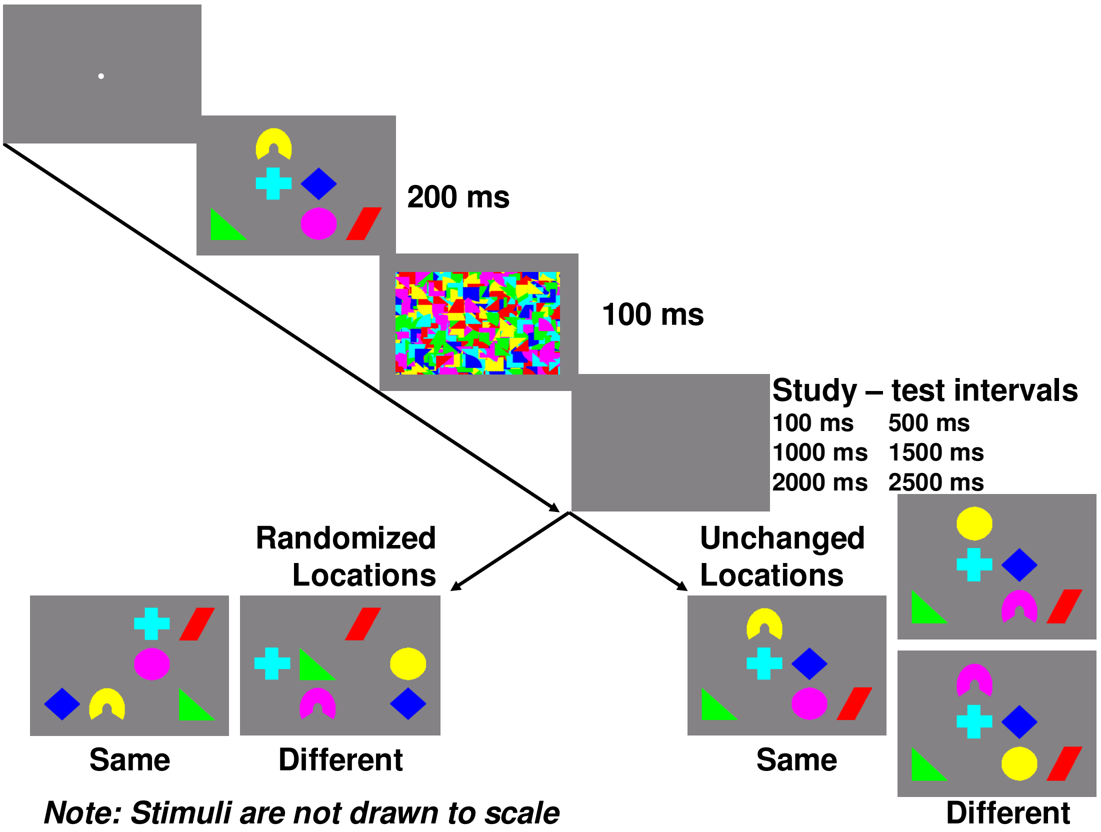
Stimuli, Design and Procedure

The stimuli, design and procedure were identical to Experiment 8, except that a pattern mask was presented for 100 ms immediately after the study display. This necessarily meant that the shortest study test interval in this experiment was 100 ms. The other study test intervals were the same as Experiment 8. The mask was a random arrangement of four parts of all the 36 possible stimuli used in the experiment. It was like a noise mask in its randomness, but like a conceptual mask in that the parts of some stimuli could be distinguished in the mask.

A different pattern was created for each of the 480 trials presented to each participant so that there was no habituation to the mask. The order of presentation of these 480 masks was randomized without replacement across participants. Figure 7.4 illustrates the procedure of this experiment.

Figure 7.4

Sequence of events in Experiment 9



Note: Stimuli are not drawn to scale

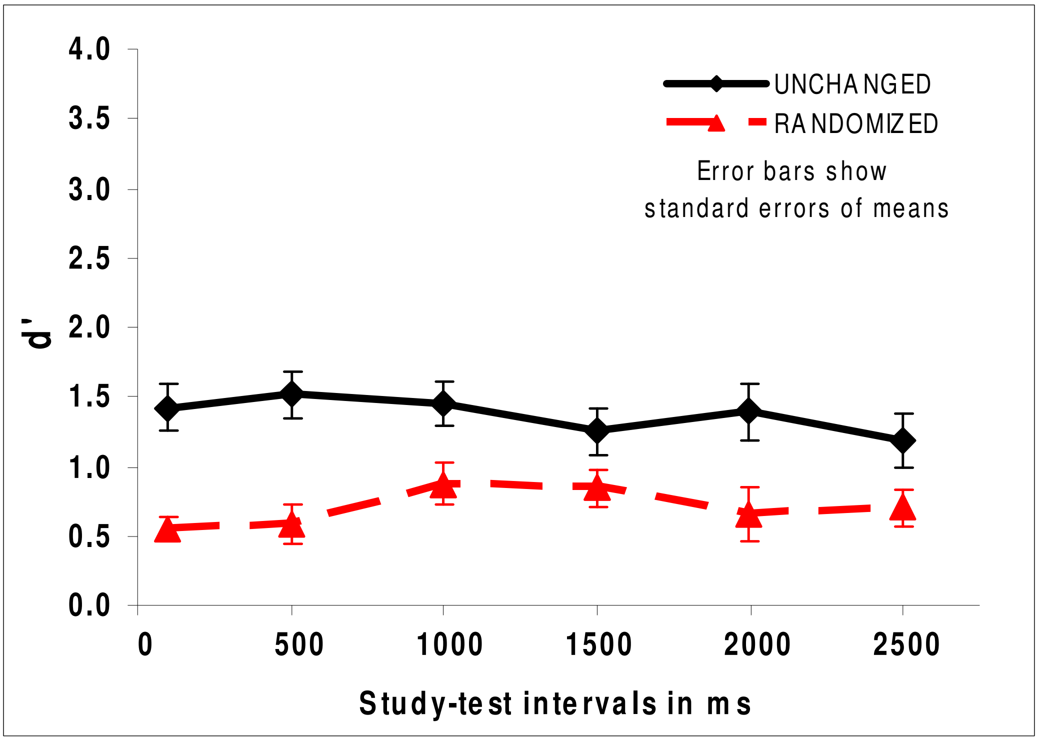
Results

Mean change detection performance calculated from d-primes across study-test intervals for the unchanged location/randomized locations conditions is shown in Figure 7.5. 2×6 ANOVA was carried out to analyze the effects of unchanged/ randomized locations and study-test intervals.

A reliable main effect of unchanged/ randomized locations was observed, $F(1,11)=46.401$, $MSE=.346$, $p<.001$, *partial* $\eta^2=.808$ showing that memory for bindings was reduced when locations were randomized between study and test as compared to the unchanged locations condition. Neither the main effect of study-test intervals, nor the interaction was significant.

Figure 7.5

Mean performance for unchanged and randomized locations for each study-test interval in Experiment 9



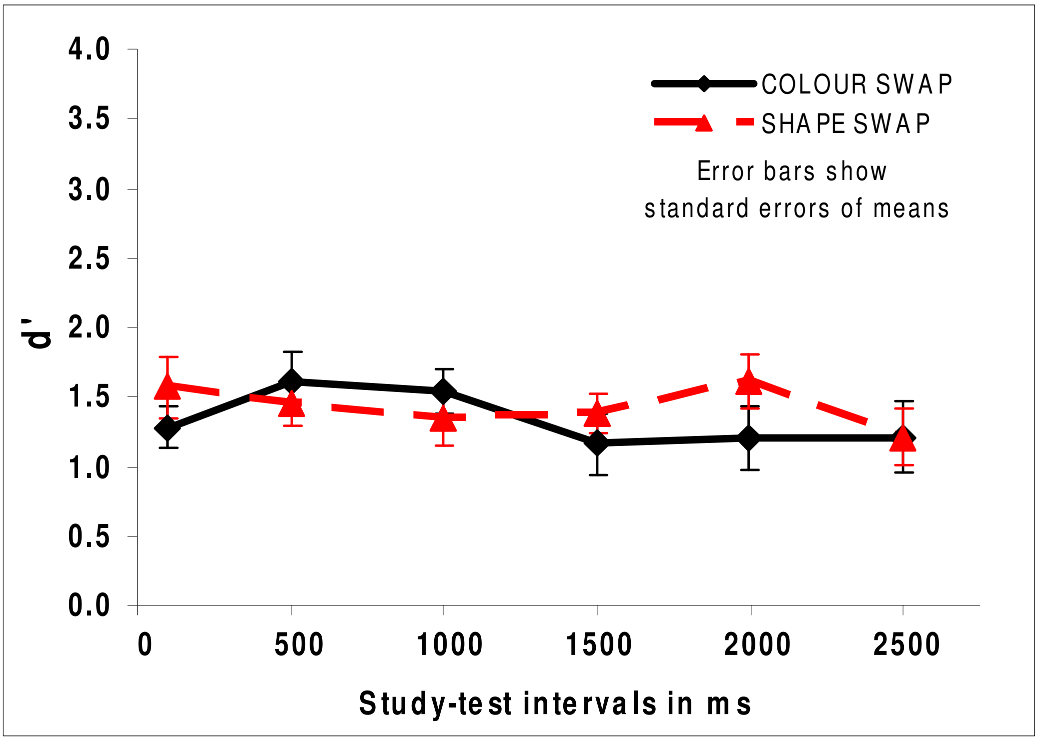
Comparing swaps

Additional analyses were conducted to test if the type of swap had any effect on the participants' performance. Analyses for swaps in the randomized locations condition did not reveal any significant effects. In the unchanged locations condition, though the main effect of swaps was not significant, there was a significant interaction between swaps and study-test intervals, $F(5,55)=2.579$, $MSE=0.143$, $p<.036$, *partial* $\eta^2=.190$. Figure 7.6 depicts the interaction.

Planned comparisons using paired samples directional t tests showed that shape swaps were detected more often than a colour swaps at 0 ms, $t(11)=2.420$, $p<.017$, and 2000 ms, $t(11)=2.768$, $p<.009$. Neither was significant with Bonferroni adjustment. Separate single degree of freedom polynomial tests for each kind of swap showed no significant trends.

Figure 7.6

Mean performance for shape swaps and colour swaps with unchanged locations for each study-test interval in Experiment 9



Discussion

The fact that the difference between unchanged and randomized conditions remained significant in Experiment 9 despite the presentation of an immediate mask, confirms that the difference between these two conditions obtained in previous experiments is not due to iconic memory alone, which was disrupted here by the immediate mask. Many researchers have shown that a backward mask presented immediately or shortly after the target stimuli only terminates the perceptual characteristics of the icon and has relatively lesser or no effect on conceptual properties, which are presumably represented by entries into VSTM (e.g., Phillips, 1974; Sligte et al., 2008; Smithson & Mollon, 2006). These stimulus representations that survive the mask apparently automatically include locations. This makes the swap easier to detect in the unchanged locations condition as compared to the randomized locations condition, leading to the difference in the performance between these two conditions.

It is also interesting to note that varying the study-test intervals in this experiment had no significant effect on the performance of the participants, and the graph shows essentially flat lines. This suggests that performance in this experiment is only a *read out* of the contents of VSTM at the different study-test intervals. Nevertheless, these representations are robust enough to be maintained in VSTM at least until 2500 ms.

EXPERIMENT 10

Experiment 10 used the same pattern mask as in Experiment 9, but it was presented after a delay of 300 ms. However, the rationale for the use of a delayed mask was quite different from Experiment 9. The idea was to allow the initial perceptual processes so that the central, conceptual processes could be studied. The assumption was that the delayed mask would interrupt the VWM processes of consolidation and inhibition that were presumably being used in this experimental task.

Many researchers have used delayed masks to interrupt the process of consolidation. Loftus et al. (1985) used a noise mask with naturalistic pictures as stimuli, immediately or after 300 ms, to find that the presence of an icon for this duration contributed information similar to an additional 100 ms of stimulus exposure. Loftus, Duncan, and Gehrig (1992) replicated and extended this work for stimuli presented for six durations ranging from 30 to 300ms, followed by a noise mask at stimulus-mask intervals ranging from 0 to 250 ms after stimulus offset. In all cases, longer stimulus exposure durations yielded more information, though the rate of decay of the icon remained the same across different stimulus-mask intervals. They concluded that consolidation continued for at least 300 ms after stimulus onset. Recent examples of the use of a delayed pattern mask to study consolidation in VWM are found in studies by Luck and his associates. Woodman and Vogel (2005) used randomly generated checkerboard masks at delays varying from 35 to 316 ms to study whether consolidation and maintenance in VWM are independent processes. Vogel et al. (2006) used pattern masks at delays from 17 to 484 ms, to conclude that consolidation of objects in VWM is at the rate of about 50 ms per item. Zhang and

Luck (2008) used masks at delays of 10 ms and 240 ms with a set size of four items to verify that durable representations in VWM are created in an all or none way for simple items. Using a change detection task, Woodman and Vogel (2008) studied the effect of a mask shown for 500 ms after stimulus-mask SOAs of 35, 105, 140, or 176 ms with the memory test after 1500 ms. Better performance for detection of colours than for shapes, orientation, or conjunctions was found. However, this distinction gradually emerged over time and was not initially evident. As such, it suggests not only selective consolidation and maintenance, but also concomitant selective inhibition.

If the mask is conceptualised as a source of interference in ongoing processes, then it would be expected to interfere with inhibition as well as consolidation. No evidence of a mask being used to interrupt the process of inhibition seems to exist in literature. Yet, associated phenomena, which are taken to be evidence for inhibition, are disrupted by tasks that draw on resources needed in the period when inhibition is presumably developing. The clearest evidence comes from studies of the preview benefit. Watson and Humphreys (1997) found that the preview benefit was reduced if a series of digits at centre screen were to be shadowed during the preview period. Humphreys et al. (2002) found the disruptive effect with an auditory secondary task. Olivers and Humphreys (2002) found that preview benefit was markedly reduced when the previewed items were presented during the attentional blink period, suggesting that if there is competition for resources required for inhibition, then the effects of inhibition in the performance of the participants is reduced. Watson and Humphreys (2005) established that irrelevant onsets disrupted the preview effect only if they shared features (colour) with the target items, thus drawing attentional resources away from the inhibitory process. Empirical evidence also suggests that inhibition is especially prevalent around 500 ms after the stimulus is first presented (Braithwaite et al., 2007; Chun & Potter, 1995; Edin et al., 2007; Humphreys et al., 2004; Maruff et al., 1999; Watson & Humphreys, 1997).

If the performance of the participants in the randomized condition in the earlier experiments does indeed show the effects of inhibition, the mask presented at 300 ms after stimulus offset and 500 ms after stimulus onset would interfere with this process, and performance at the initial test at 400 ms would be better as compared to performance at the initial test at 0 ms in Experiment 8. This would happen because the reduction in performance at 0 ms due to inhibition that was observed in earlier experiments with no mask would not happen if the delayed mask interrupts the process of inhibition that caused this reduction in the first place. Thus, a rebound of performance will occur with the delayed mask as compared to Experiment 8 as well as Experiment 9. As mentioned in the introduction to this series of experiments, this specific prediction will be tested with planned comparisons.

A similar upsurge is not expected in the unchanged locations condition simply because inhibition is not used to the same extent in this condition and is certainly not manifest in the performance in the same way. Among others, Watson and Humphreys (1997) and Woodman and Luck (2007) have proposed that inhibition is used only when required. In the unchanged locations condition, the delayed mask would remove the effects of iconic memory to the extent that it affects performance at 300 ms offset. Following earlier studies which have used masks to interrupt consolidation (e.g., Vogel et al., 2006) performance would manifest the information that is present in VSTM 300 ms after stimulus offset.

To summarize, the shorter study test intervals seem to be the primary arena for the interplay of three forces – iconic storage, consolidation of the binding of relevant features, and inhibitory control of irrelevant information. The mask would compete for resources with these forces and consequently have the greatest impact on the dominant factor in each condition. In the unchanged locations condition, it would interfere with, delete the effect of iconic memory, and stop further consolidation into VWM. In the randomized locations condition, the mask would interfere with and delete the effect of inhibition from the performance of the participants. Thus, it is predicted that both conditions in Experiment 10 would manifest the information that is present in VSTM as a result of selective consolidation until 300 ms after stimulus offset. Thereafter, the trend for the randomized and unchanged conditions should be similar in that both conditions would show further maintenance or forgetting of VSTM representations.

Participants

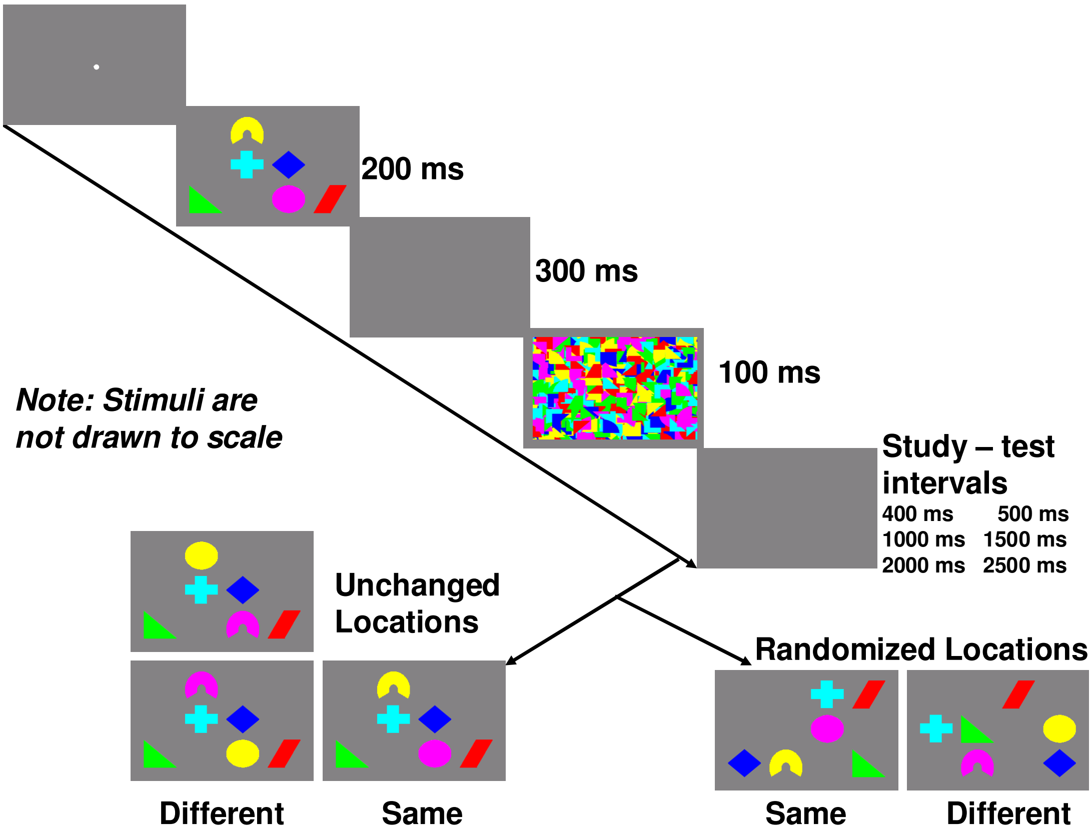
Twelve students (6 men and 6 women) in the age range 18-25 years were given an honorarium of £10 for their participation in the experiment.

Stimuli, Design and Procedure

These were identical to Experiment 9, except that the mask of 100 ms duration was presented after a delay of 300 ms after the study display, and thus the initial test occurred at 400 ms. Figure 7.7 illustrates the procedure.

Figure 7.7

Sequence of events in Experiment 10

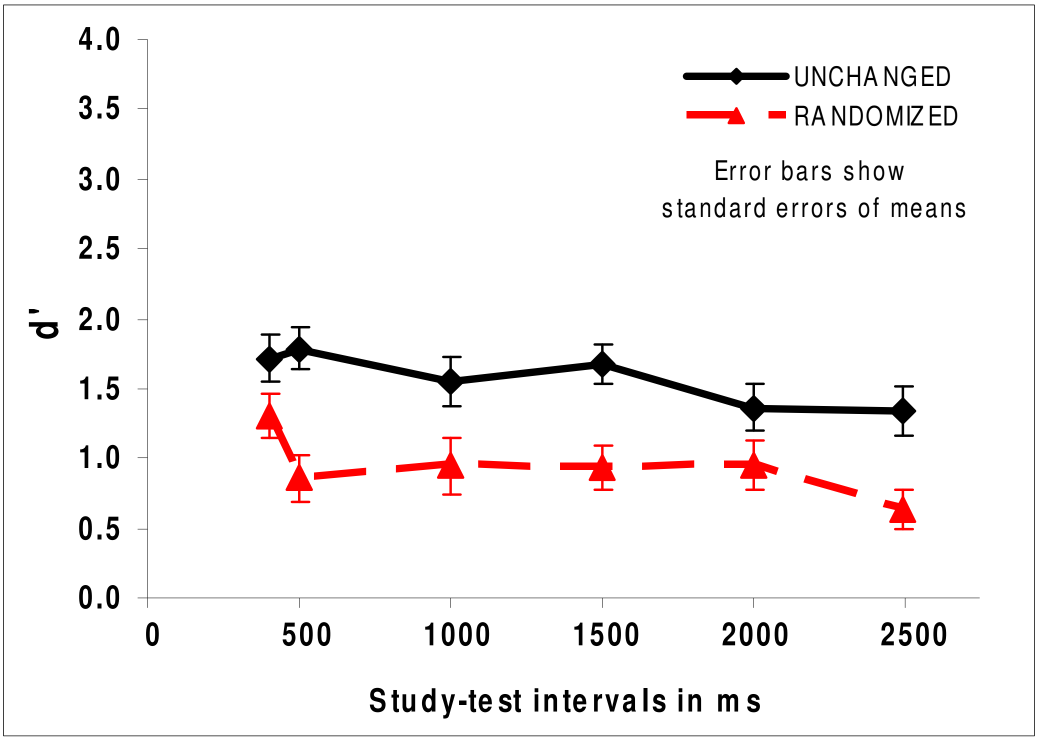


Results

Mean change detection performance calculated from d-primes across study-test intervals and for the unchanged location/randomized locations conditions is shown in Figure 7.8. A 2×6 repeated measures ANOVA was done to analyse the effects of unchanged/randomized locations and study-test intervals. A reliable main effect of unchanged/randomized locations was observed, $F(1,11)=36.724$, $MSE=0.391$, $p<.001$, *partial* $\eta^2=.770$, because memory for bindings was reduced when locations of stimuli were randomized from study to test. The main effect of study-test intervals was also reliable, $F(5,55)=3.585$, $MSE=0.205$, $p<.007$, *partial* $\eta^2= =.246$, indicating that accurate detection of bindings varied across study-test intervals, gradually decreasing over time. However, there was no significant interaction. This is clearly depicted in Figure 7.8.

Figure 7.8

Mean performance for unchanged and randomized locations for each study-test interval in Experiment 10



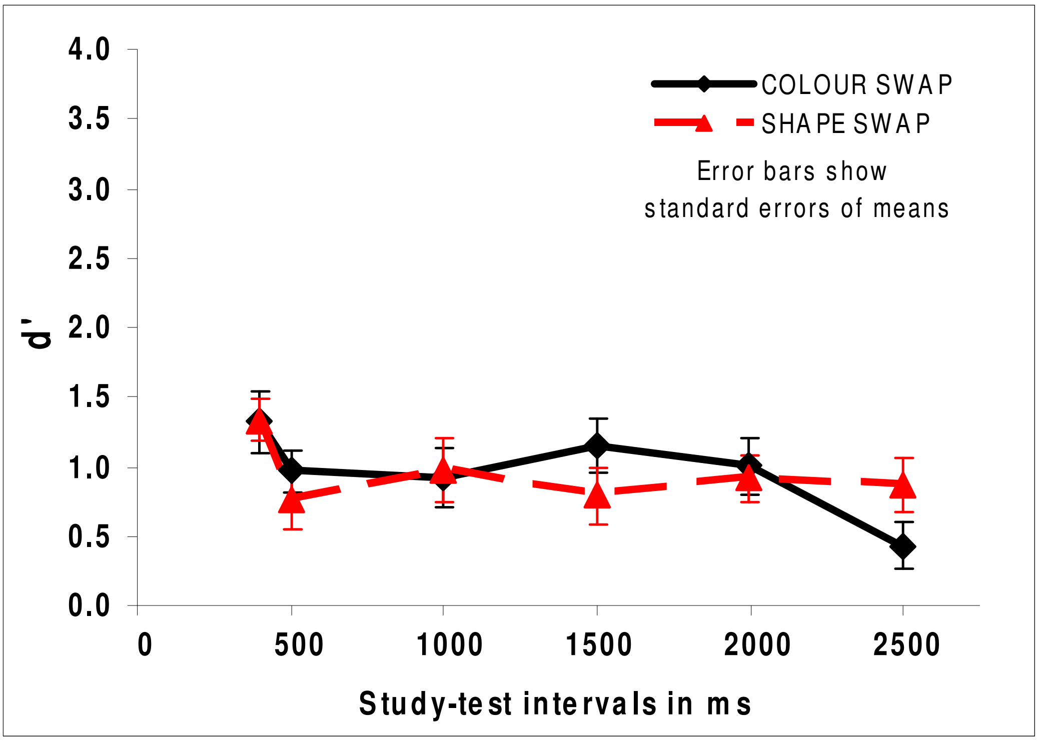
Separate single degree of freedom polynomial tests for unchanged locations showed a significant linear trend, $F(1,11)=5.210$, $MSE=0.294$, $p<.043$, *partial* $\eta^2=.321$. In the randomized locations condition the linear, $F(1,11)=26.922$, $MSE=0.062$, $p<.001$, *partial* $\eta^2=.710$, and cubic $F(1,11)=13.988$, $MSE=0.076$, $p<.003$, *partial* $\eta^2=.560$, trends were significant.

Comparing swaps

Additional analyses were conducted to test if the type of swap had any effect on the participants' performance. In the unchanged locations conditions, neither the main effect for swaps, nor the swap × study-test interval interaction effect was significant. In the randomized locations condition too, the main effect of swaps was not significant, though the swap × study-test interval interaction effect approached significance, $F(5,55)=2.327$, $MSE=0.186$, $p<.055$, *partial* $\eta^2=.175$. Figure 7.9 depicts this interaction.

Figure 7.9

Mean performance for shape swaps and colour swaps with randomized locations for each study-test interval in Experiment 10



Planned comparisons using paired samples t tests with Bonferroni adjustment showed that shape swaps were detected more often than a colour swaps at 2500 ms, $t(11)=2.225$, $p<.048$. Considering that none of the earlier experiments showed significant differences between shape swap and colour swap in the randomized condition, this single difference could have occurred by chance, and is otherwise inexplicable. The tendency towards a significant interaction is more likely due to different trends for colour and shape swaps. Separate single degree of freedom polynomial tests for each kind of swap showed that for colour swaps, linear $F(1,11)=34.781$, $MSE=0.180$, $p<.001$, *partial* $\eta^2=.760$, and cubic, $F(1,11)=11.747$, $MSE=0.180$, $p<.006$, *partial* $\eta^2=.516$, trends were significant, but for shape swaps only the linear trend, $F(1,11)=5.202$, $MSE=0.144$, $p<.043$, *partial* $\eta^2=.321$, was significant.

Discussion

Performance levels were overall higher in the unchanged locations condition, as compared to the randomized locations condition as Figure 7.8 shows. This suggests that the preserved representations in VSTM probably include some information about locations which aided change detection in the unchanged locations condition. The main effect of study-test intervals was also significant, performance gradually decreasing from the shortest to the longest study- test interval.

The lack of significance of the interaction in this experiment, contrary to all previous experiments is clear in the graph where the slope of the trend in unchanged as well as randomized conditions is negative, and is driven by the statistically similar performance of the participants at the initial study-test interval. The implications of this result will be discussed after the results reported in the next section.

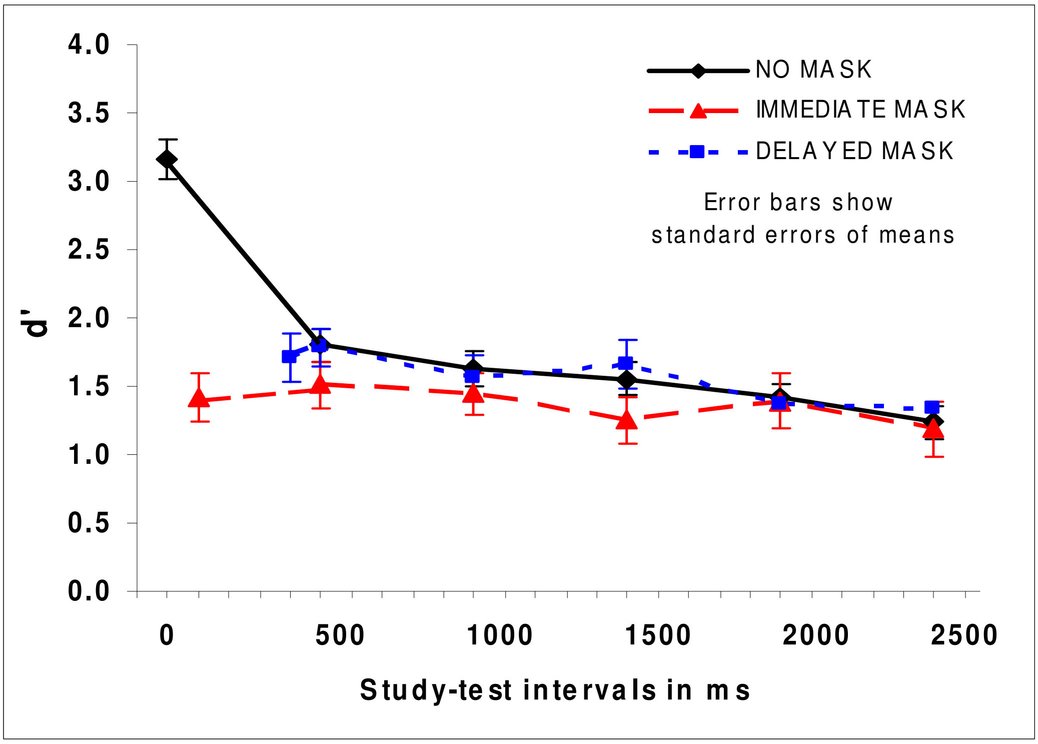
COMPARING EXPERIMENTS 8, 9, AND 10

The primary motivation for Experiments 8, 9 and 10 was to compare the performance of the participants under no mask, immediate mask, and delayed mask conditions with unchanged and randomized locations at the various study-test intervals. It is recognised that the three experiments have a different initial study-test interval as a necessary concomitant of the 100 ms mask being given immediately and after a 300 ms delay. Thus, whereas the initial study-test interval for Experiment 8 was 0 ms with no mask, it was 100 ms for the Experiment 9 where an immediate mask was used, and it was 400 ms where a delayed mask was used. The graphs show this difference clearly, as they are drawn to a time-scaled x-axis. The statistical analysis reported below treated these as equivalent, for the trend of changes in performance was of interest. Nevertheless, in respect of these differences in the initial study-test interval, separate analyses for the initial study-test interval alone, and the later study-test intervals (500 to 2500 ms) were also carried out. The one-way analysis comparing the three experiments separately for unchanged and randomized conditions also allowed planned comparisons using independent samples t tests with Bonferroni adjustment, as indicated in the introduction to this series of experiments.

A 3×2×6 ANOVA with experiments (between subjects), unchanged/randomized locations (repeated measures), and study-test intervals (repeated measures) was carried out to compare performance across experiments. There was a significant three way interaction, $F(10,165)=8.403$, $MSE=0.159$, $p<.001$, *partial* $\eta^2=.337$, and significant two way interactions between unchanged/randomized locations and experiments, $F(2,33)=6.935$, $MSE=0.312$, $p<.003$, *partial* $\eta^2=.296$, between study-test intervals and experiments, $F(10,165)=3.250$, $MSE=0.210$, $p<.001$, *partial* $\eta^2=.165$, and between unchanged/randomized locations and study-test intervals, $F(5,165)=9.930$, $MSE=0.159$, $p<.001$, *partial* $\eta^2=.231$. The main effect for experiments was not significant, but the effects were significant for unchanged/randomized location, $F(1,33)=216.470$, $MSE=0.312$, $p<.001$, *partial* $\eta^2=.868$, and study-test intervals, $F(3.788,125.088)=8.298$, $MSE=0.277$, $p<.001$, *partial* $\eta^2=.201$, with Greenhouse-Geisser correction applied.

To investigate the three-way interaction further, two way ANOVAs were conducted separately under unchanged and randomized locations conditions. The 3 × 6 ANOVA with experiments as the between subjects variable and study-test intervals as the within subjects variable for unchanged locations revealed significant main effects for experiments, $F(2,33)=4.399$, $MSE=0.762$, $p<.020$, *partial* $\eta^2=.210$, and study-test intervals, $F(5,165)=15.112$, $MSE=0.205$, $p<.001$, *partial* $\eta^2=.314$. There was also a significant interaction between experiments and study-test intervals, $F(10,165)=7.873$, $MSE=0.205$, $p<.001$, *partial* $\eta^2=.323$. Figure 7.10 shows the results.

Figure 7.10
Mean performance with unchanged locations
for each study-test interval in Experiments 8, 9, and 10



The interaction was further explored by conducting single degree of freedom polynomial tests separately for each experiment. In Experiment 8, performance across study-test intervals was characterized by reliable negative-slope linear $F(1,11)=99.034$, $MSE=.202$, $p<.001$, *partial* $\eta^2=.900$, quadratic, $F(1,11)=48.612$, $MSE=.105$, $p<.001$, *partial* $\eta^2=.815$, cubic, $F(1,11)=12.958$, $MSE=.230$, $p<.004$, *partial* $\eta^2=.541$, and quartic trend $F(1,11)=8.720$, $MSE=.058$, $p<.001$, *partial* $\eta^2=.442$. For Experiment 9, no significant trends were found. In Experiment 10, performance across study-test intervals was characterized only by a reliable negative-slope linear trend, $F(1,11)=5.210$, $MSE=.294$, $p<.043$, *partial* $\eta^2=.321$.

One way analysis, comparing experiments at the initial study-test interval was carried out, followed by planned comparisons using independent samples t tests with Bonferroni adjustment. The result showed a significant difference between experiments, $F(2,33)=32.821$, $MSE=.316$, $p<.001$. Performance with no masks in Experiment 8 was significantly better than when an immediate mask, $t(22) = 7.683$, $p<.001$, or delayed mask, $t(22) = 6.557$, $p<.001$, was used, with no difference between the latter two. It should be recognized, however, that this one-way analysis does not consider the time difference in the initial study-test interval in the three experiments. A clearer picture emerges from Figure 7.10. In Experiment 9, the immediate mask disrupts iconic storage relative to performance in Experiment 8 at 100 ms post stimulus. In Experiment 10, performance after the delayed mask (400 ms after stimulus offset) is very similar to what might be assumed from linear interpolation in the plot of performance in Experiment 8 at 400 ms, and is very similar to that actually found for test at a 500 ms study-test interval without a mask. In other words, performance after delayed mask is similar to what was found for a similar delay without a mask in Experiment 8, and there appears no effect of a delayed mask in this condition as compared to the baseline performance without a mask. Thus in this condition, only the immediate mask had an effect on performance.

A separate 3 ×5 ANOVA was also carried out to test if performance differed in the three experiments from 500 to 2500 ms. Neither, the main effect of experiments, nor the interaction with study-test intervals was significant. However, the overall effect of study-test intervals was significant, $F(4,132)=5.486$, $MSE=0.181$, $p<.001$, *partial* $\eta^2=.143$, with only a linear trend with a negative slope, $F(1,33)=15.069$, $MSE=0.258$, $p<.001$, *partial* $\eta^2=.313$, that was significant. This suggests that performance manifests a steadily decaying trace from VSTM.

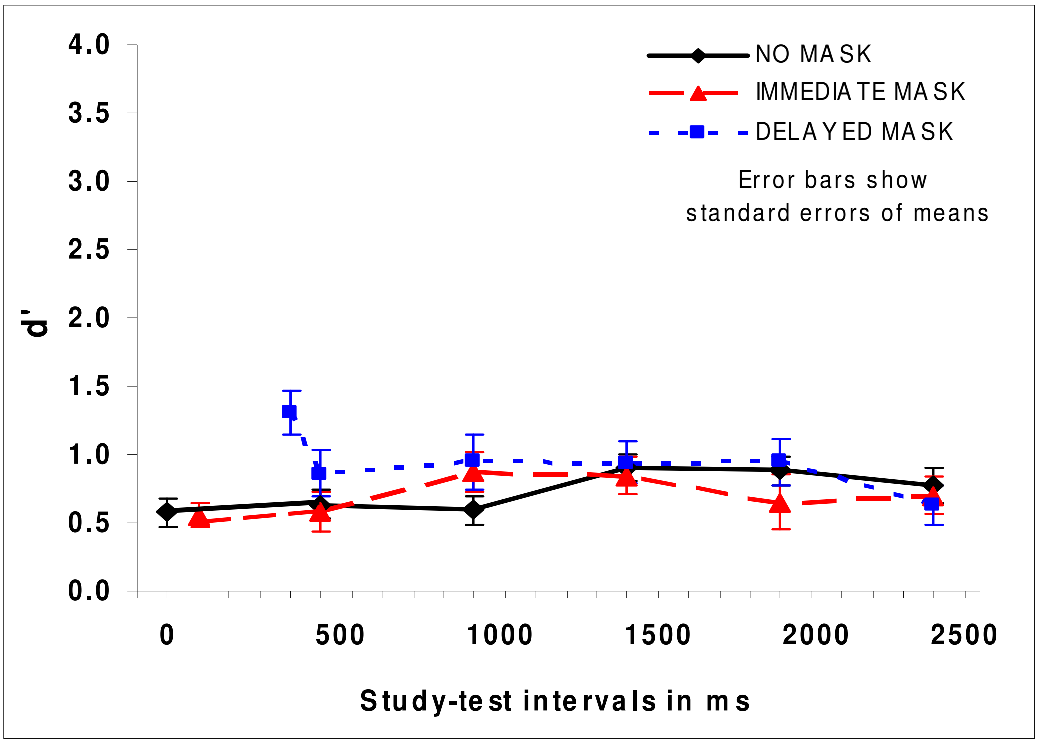
One may infer that in the unchanged locations condition in Experiment 8, performance is driven by iconic memory at the shortest study-test interval and thereafter it shows a gradual forgetting from VSTM. The immediate mask disrupts iconic storage, so performance is dictated only by the contents of VSTM, which are maintained across the study-test intervals in Experiment 9. Performance is slightly but not significantly higher in Experiment 10 than in Experiment 9, because the delayed mask allows a little more consolidation and more information to be transferred into VSTM as compared to an immediate mask.

The 3 × 6 ANOVA for randomized locations with experiments as the between subjects variable and study test intervals as the within subjects variable found no significant main effects, but a significant interaction effect, $F(10,165)=2.478$, $MSE=0.164$, $p<.009$, *partial* $\eta^2=.131$. Figure 7.11 shows the results.

Figure 7.11

Mean performance with randomized locations

for each study-test interval in Experiments 8, 9, and 10



The interaction was further investigated using separate single degree of freedom polynomial tests within each experiment. For Experiment 8, in consonance with previous experiments 1, 2, and 5, performance was characterized by a positive slope trend, $F(1,11)=5.547$, $MSE=0.130$, $p<.038$, *partial* $\eta^2=.335$, which was linear. For

Experiment 9, no significant trends were found. For the Experiment 10, significant negative slope linear, $F(1,11)=26.922$, $MSE=0.062$, $p<.001$, *partial* $\eta^2=.710$, and cubic, $F(1,11)=13.988$, $MSE=0.076$, $p<.003$, *partial* $\eta^2=.560$, trends were observed.

One way analysis, comparing experiments at the initial study-test interval was carried out, followed by planned comparisons using independent samples t tests with Bonferroni adjustment. The result showed a significant difference between Experiments, $F(2,33)=12.752$, $MSE=.173$, $p<.001$. Performance with delayed masks (Experiment 10) was significantly different from performance with no masks in Experiment 8, $t(22)=3.854$, $p<.001$ and performance with an immediate mask in Experiment 9, $t(22)=4.240$, $p<.001$, with no significant difference between the latter two. Indeed, post hoc paired comparisons with Bonferroni adjustment showed that this performance was also significantly higher than the performance at 500 ms with no mask, $t(22)=3.604$, $p<.002$, and immediate mask, $t(22)=3.354$, $p<.003$.

A separate 3(Experiment) ×5(Study-test interval) ANOVA was also carried out to check if performance differed in the three experiments from 500 to 2500 ms. Neither the main effect of experiments, nor the interaction with study-test intervals was significant.

This result clearly shows that in the randomized locations condition, performance is not driven by iconic memory, for the immediate mask has virtually no effect as compared to the baseline performance in Experiment 8. This is in contrast to its effect in the unchanged locations condition. It is the delayed mask, which is effective in the randomized condition, performance being significantly different from Experiment 8 as well as Experiment 9.

In contrast to the usual masking effect that decreases performance, however, there is an *increase* in performance after the delayed mask. This increase is not only more than the performance in Experiments 8 and 9, but is also more than the asymptotic performance at the later study-test intervals in Experiment 10. As noted in the discussion of Experiment 10, this upsurge results in statistically no difference between unchanged and randomized location conditions when performance was tested at 0 ms. This result also contradicts the results obtained in this condition in all previous experiments with locations (Experiments 1, 2, 5 and 8) where the lowest performance was found in this condition.

This increase is interpreted as showing the interfering effect of the delayed mask on the VWM process of inhibition which was evident in the earlier Experiments 1, 2, 5, and 8. This process maintains a selection of the total set of stimuli in terms of relevant features, and actively inhibits irrelevant features as well as the unselected stimuli. It is this inhibitory control process, which is interrupted by the delayed mask resulting in performance levels higher than when there is no mask or an immediate mask at the initial test, with a decrease to asymptotic performance based on representations maintained in VSTM thereafter. The implications of this rebound in performance are further analysed in the general discussion.

GENERAL DISCUSSION

The use of masks in both Experiments 9 and 10 was effective and revealed a complex but interesting pattern of results.

The immediate mask had the greatest effect in the unchanged locations condition, particularly at the shorter study-test intervals, which presumably benefit most from the presence of the icon in Experiment 8 and earlier experiments. Nevertheless, the effect of iconic memory alone cannot explain the results of these experiments.

The importance of consolidation is evident from the slight, but non-significant, increase in performance in Experiment 10 as compared to Experiment 9, at the various study-test intervals, in both randomized and unchanged conditions. The delayed mask presumably allowed a slightly greater amount of consolidation of information into VSTM as compared to the immediate mask. However, as noted in the review in Chapter 2, consolidation is a very slow process and 300 ms more of processing time did not yield a significant difference.

The results also showed that performance in the randomized condition is higher when tested at 400 ms after a delayed mask, than in the immediate mask condition, which does not allow the beneficial effect of consolidation or transfer of information from the icon to VSTM. Sligte et al. (2008) have recently shown that a very large number of items are present in 'fragile' VSTM for a considerable time after stimulus offset, and certainly beyond the duration that iconic memory is traditionally held to last. But, the consolidation interpretation of the result at the initial test at 400 ms in the randomized condition in Experiment 10 cannot be reconciled with the same condition in Experiment 8. Why is the large effect of consolidation, higher than the asymptotic performance at the later study-test intervals, not evident in Experiment 8, or indeed in every other condition in every other experiment? Surely, the mask cannot *create* the effects of consolidation in the randomized locations condition of Experiment 10 alone?

Instead, if the mask is conceptualised essentially as an interfering mechanism with whatever process is prevalent at that time, then it is possible that in the randomized condition, it interferes with the inhibitory process that is dominant in this condition. When this happens, performance rebounds, dictated only by the bindings of relevant features in VSTM at that time. Maybe it is not right to invoke inhibition as an explanation whenever performance is seen to fall below a baseline condition (MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003). But the deduction here is supported by the result in Experiment 10. It rests on a significant difference obtained due to the presentation of the mask in one experiment and not in the other. It does not allow alternative explanations. This result forces the conclusion that there must be a process of active inhibition or suppression, that was most clearly evident in previous experiments when locations were randomized, and it is this process that the mask interrupts when presented at 300 ms after stimulus display offset. Thus, this performance is driven by a recovery from inhibition and selective consolidation of bindings of relevant features into VSTM. Thereafter, performance is dictated by the representations maintained in and gradually lost from in VSTM.

Considering *what* is being suppressed in the randomized locations condition, one has to imagine how the participants are doing the task. Faced with six stimuli in the study display, a few are selected and maintained in memory. They do not know which ones to select because any two might change. Indeed, best performance can be ensured only if they try to remember as many bindings as they can. Nevertheless, they do know that the location of the stimuli is irrelevant right from the outset, through task instructions as well as the practice trials with randomized locations. Therefore, this feature is actively suppressed and deleted from the representation. The most efficient strategy dictates that the maximum possible information is maintained in VWM. Since the task taxes the limited storage capacity of the visual store, it is important to select and store only relevant information in the form of bindings; but it is also equally important to delete unwanted features. This process of deletion, however takes time. It is presumably at its peak at around 300 ms after stimulus offset or 500 ms after stimulus onset as shown by previous studies of preview benefit, attentional blink, and physiological evidence from EEG studies extensively reviewed in Chapter 2 in the section on inhibition. This inhibitory process is interrupted by the delayed mask in Experiment 10, such that the performance is then determined only by the bindings that are present in VWM because of selective consolidation until that time.

Taken together, the results of the three experiments reported in this chapter confirm that the performance of the participants in earlier experiments is determined by the interplay of forgetting from iconic memory, selective consolidation of relevant features and inhibition of irrelevant features by VWM.

CHAPTER 8

EXPERIMENTS 11, 12, 13, AND 14

The motivation for the experiments reported in this chapter was to explore further the nature of top-down process of inhibition to study how far it is contingent on the initial processes that operate at the time of the encoding of the stimulus. Two encoding factors were considered – study-display duration, and simultaneous vs. sequential presentation of stimuli. Specifically, the aim was to investigate how the interaction obtained in earlier experiments was affected by these encoding factors. The study-display durations chosen were 200, 900, and 1500 ms. Only two study-test intervals, 0 and 2000 ms, were used. Previous experiments had shown that these two intervals would capture the maximum and minimum difference between the unchanged and randomized locations conditions. In addition, the pattern of results for the intervening study-test intervals was already known.

In all the experiments reported in the previous chapters, the study-display was shown for 200 ms, and it could be argued that this study-display duration was insufficient to encode all the six stimuli in the display. Research evidence clearly suggests that increasing the study-display duration should generally improve performance though there is a threshold before performance can 'liftoff' and there is a duration at which it reaches an asymptote (Busey & Loftus, 1994; Loftus & Maclean, 1999). Using a change detection paradigm, Pashler (1988) reported a significant but small increase in performance for 10 consonants presented for 100, 300, and 500 ms, with the test display presented after 67 ms. Liu and Jiang (2005) asked participants to remember objects in scene images to find that 250 ms allows only about one object to be retained in memory whereas much more time (up to 16 seconds) was required to retain more veridical details of about five objects. The time-based resource-sharing model of WM (Barrouillet et al., 2004; Barrouillet & Camos, 2007) also suggests that increasing the study-display duration should improve performance for it allows more time for encoding and processing of stimuli. Thus, it was predicted that increasing the study-display duration would generally improve performance.

The focus in the present experiments was, however, not only to study what happens due to an increase in the study-display duration beyond 200 ms, but also to test whether this increase modulates the interaction obtained between the unchanged and randomized conditions across study-test intervals. Assuming that an inhibitory mechanism is indeed at work in the previous experiments, it was of interest to identify *when* this mechanism came into play. This was particularly important in the light of evidence from fMRI and ERP studies, which show that irrelevant features are also activated along with the relevant ones (O'Craven et al.,1999a, 1999b; Schoenfeld et al., 2003; Winkler et al., 2005), and inhibition occurs later. In contrast, Hommel (2005) has proposed that task-relevant features are more likely to be integrated into an object than task-irrelevant ones at the encoding stage itself.

If the inhibitory mechanism operates at the time of encoding, then increasing the study-display duration would allow inhibition to proceed during the presentation of the study display itself, and performance measured after study-display durations of 900 ms or 1500 ms would be similar to what was observed at these time intervals in the earlier experiments. This would consequently decrease the gap between the unchanged and randomized locations conditions at 0 ms. This would also necessarily predict a significant three factor interaction among unchanged/randomized locations, study-test intervals, and study-display durations, because study-display duration would modulate the interaction between locations and study-test intervals obtained in the earlier Experiments 1, 2, 5, and 8.

However, if inhibition is a post-encoding factor, working as a top-down factor in tandem with the gradual process of consolidation, after all the features of the stimuli are initially bundled together as a weak representation, then increasing the study-display duration should not affect the amount of disruption experienced, expressed by the gap between the two experimental conditions at 0 ms and 2000 ms.

The second encoding factor under consideration in this chapter is simultaneous vs. sequential presentation. With regard to the mechanism of attention, which implements top-down control, Mackworth (1962) suggested that simultaneous presentation allows voluntary and flexible allocation of spatial attention and rescanning, and therefore results in better performance. In contrast, sequential presentation imposes an orderly sequence that directs attention, and precludes rescanning, especially if previous stimuli vanish as new ones are presented. Evidence from fMRI studies reviewed in Chapter 2 also suggests that inhibition of irrelevant information shows up only in simultaneous presentation conditions and is not evident with sequential presentation (Kastner et al., 1998; Shafritz et al., 2002). However, behavioural studies have shown equivocal results, often showing no differences between simultaneous and sequential presentation unless cognitive load exceeds capacity. This has led researchers to postulate that when items are few, even simultaneously presented stimuli are processed one by one, and thus performance is similar. A greater number of stimuli makes configural encoding possible and hence makes simultaneous performance better (Dent & Smyth, 2006; Igel & Harvey, 1991; Lecerf & De Ribaupierre, 2005; Zimmer et al., 2003). A detailed review of these studies appears in Chapter 2.

Sequential presentation has often been used with change detection tasks by researchers in the area of VWM to prevent configural encoding of the stimuli in the initial test display (e.g., Alvarez & Cavanagh, 2008; Woodman & Luck, 2004). With regard to binding, in the domain of perception, many studies have shown either, the superiority of simultaneous presentation over sequential presentation, or similarity between the two conditions (e.g., Fahle & Koch, 1995).

Specifically testing memory for colour-shape bindings, Allen et al. (2006) reported better performance with simultaneous than sequential presentation. Intending to study the fragile nature of bindings, they presented four stimuli one by one for 250 ms with blank intervals of the same duration between the stimuli, thus making the exposure duration for each single stimulus equivalent to the total exposure with simultaneous presentation of all four stimuli. All stimuli were presented in four set locations, followed by a single item probe. In their experiment, however, not only was the set size well within capacity, relational encoding was presumably precluded in the sequential condition. Thus, the advantage of simultaneous presentation might also have occurred due to configural encoding.

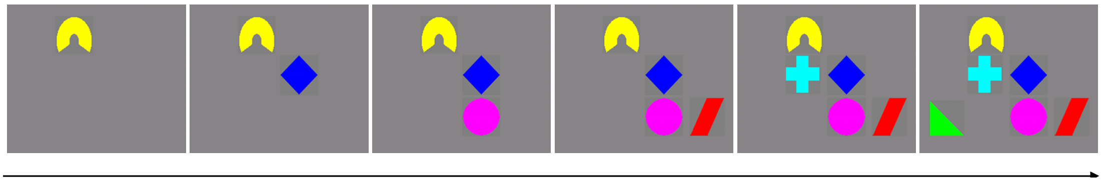
Two recent studies have shown superior performance with sequential presentation. Fougnie and Marois (2009) tested memory for colour-shape bindings with a single probe. Using the dual task paradigm, they found greater interference from an attention-demanding task with simultaneous rather than sequential presentation, suggesting that maintaining bindings in VWM in the face of interference is more attention demanding. In their study, the display consisted of only three items, was shown for 400 ms and the test was after 6800 ms. The small number of stimuli to be retained would not have required configural encoding, affording no advantage to simultaneous presentation. Further, as sequential presentation makes stimuli more distinct than simultaneous presentation, they might have been easier to retain over the long study-test interval. Using real life scenarios to test memory for objects, Yamamoto and Shelton (2009) have shown that sequential presentation yields better performance than simultaneous presentation for it allows focal attention to be directed at stimulus objects. In both these studies, the focus was clearly on *maintaining* bound objects in memory. In such cases, sequential presentation might be superior for it simply increases the distinctiveness of stimuli, and the negative effects of crowding are precluded. In addition, benefits might accrue in the sequential condition because it provides an additional code for encoding and remembering stimuli in VWM.

Taken together, these studies indicate that research evidence is equivocal regarding the relative superiority of sequential and simultaneous presentation. To enable the contrast between sequential presentation, that provides an additional code without completely destroying configural encoding, versus sequential presentation that obliterates configural encoding, two experiments were designed with sequential presentation. Both could be also contrasted with simultaneous presentation in Experiment 11. Experiment 12 presented stimuli one by one to gradually build up the study display, thereby retaining configural information. Experiment 13 presented stimuli one at a time such that each stimulus vanished as the next was presented. Figure 8.1 illustrates both types of sequential presentations.

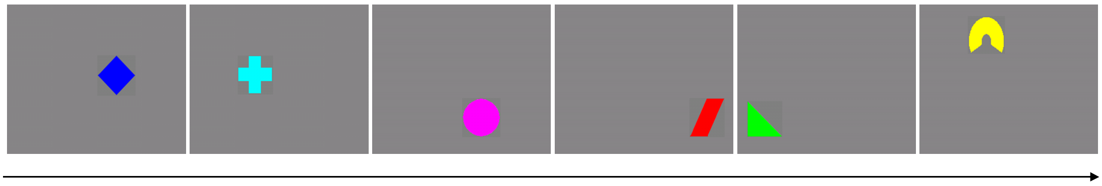
Figure 8.1

Sequential presentation of stimuli

To build up the Study-display in Experiment 12



One at a time sequential presentation of stimuli in Experiment 13



Note: Stimuli are not drawn to scale

In all experiments, the test display comprised the presentation of all stimuli together. To the extent that performance is affected by configural encoding, it was expected that the pattern of results would differ in these experiments. When locations are unchanged, and hence configural encoding is beneficial, participants' performance should benefit from simultaneous presentation, but when locations are randomized, configural encoding actually hampers performance and thus simultaneous performance might be worse.

The question here is not really, whether simultaneous presentation is better or worse than sequential presentation. Rather the focus is on how the type of presentation influences the interaction between unchanged and randomized conditions. Since the immediate masking experiment reported in Chapter 7 had shown that configural encoding allowed by iconic memory was a greater factor in the unchanged locations condition at the initial study-test interval, it was specifically expected that performance in the unchanged condition at 0 ms would deteriorate from Experiment 11 with simultaneous presentation, through Experiment 12 with sequential presentation with configural information available as stimuli remain on the screen to build up the study display, to Experiment 13 which precludes configural encoding by never presenting all stimuli together. This would also change the overall pattern of interaction obtained in the three experiments and yield a significant three-factor interaction among experiments, unchanged/randomized locations, and study-test intervals.

The two experiments with sequential presentation, Experiments 12 and 13, yielded an opportunity to explore serial position effects. Serial position effects may occur due to a variety of reasons extensively reviewed in Chapter 2. In the present experiment, if no serial position effects were obtained, it would indicate that stimuli were being essentially processed as a whole pattern, much the same as with simultaneous presentation, or that the participants randomly selected a few of the six stimuli and focussed on those, using object focussed attention. If only a primacy effect is shown, it would imply that the initial stimuli were processed and rehearsed, but not the last few. If only the recency effect is shown, it would be evidence that the initial stimuli were overwritten by the last few stimuli. If both primacy and recency are shown, it would show that stimuli are activated and encoded in the context of their serial position in a sequence.

To anticipate the results, serial position effects were obtained. Formal ANOVA on the data from Experiments 11 and 12 to test higher order interactions was precluded because stimuli were swapped randomly, and in some of the experimental conditions, at least one subject was not tested with one of the 15 swap combinations. Experiment 14 was designed to overcome this limitation. It ensured that each swap was presented an equal number of times to all participants. The experiment tested the effects of study-test intervals and study-display durations on serial position effects. Since it was a partial replication of Experiment 13, results were expected to follow those from Experiment 13. The specific hypotheses are detailed in the introduction to Experiment 14. The primary interest was to explore the interactions.

To recap, Experiment 11 tested the effect of increasing the study-display duration on swap detection performance for simultaneously presented stimuli. Experiments 12 and 13 do the same for sequentially presented stimuli. Experiment 14 was a partial replication of Experiment 13. To design a stringent test of the influence of these factors, blocked presentation was used. Thus, it was being tested whether these encoding factors affected performance despite the maximum task focus that is allowed by blocked presentation, and while participants devoted maximum resources for top-down inhibitory control rather than diverting them for switching sets.

EXPERIMENT 11

Experiment 11 was designed to test the effect of increasing the study-display durations on swap detection performance shown by the participants in the previous experiments with simultaneous presentation. The study-displays were shown for 200 ms, 900 ms, and 1500 ms. Their effect on the participants' performance was tested at the study-test intervals of 0 and 2000 ms. It was predicted that increasing the study-display duration would, in general, lead to superior performance.

Competing predictions were tested for the effect of increasing study-display duration on the gap between the performance for unchanged and randomized conditions obtained at 0 and 2000 ms. If inhibition occurred during encoding, increasing the study-display duration should reduce the gap at 0 ms, and yield a significant interaction between study-display durations and study-test intervals. If inhibition was a post-encoding factor, then increasing study-display duration should have no differential effect on performance at 0 and 2000 ms, and the interaction between study-display durations and study-test intervals would not be significant.

Participants

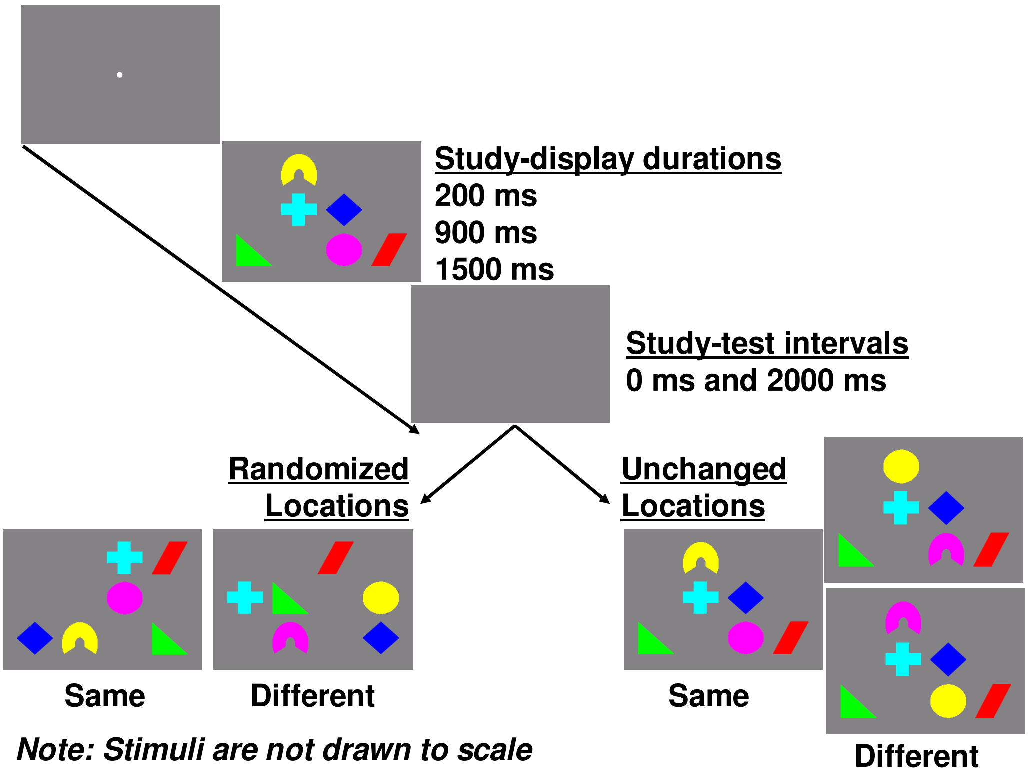
Twelve students (6 men and 6 women) in the age range 18-25 years were given an honorarium of £10 for their participation in the experiment.

Stimuli, Design, and Procedure

The stimuli used were identical to Experiments 1, 2, 5, and 8. The experiment was designed as a 2×2×3 factorial experiment with repeated measures on all factors. Figure 8.2 illustrates the procedure.

Figure 8.2

Sequence of events in Experiment 11



Note: Stimuli are not drawn to scale

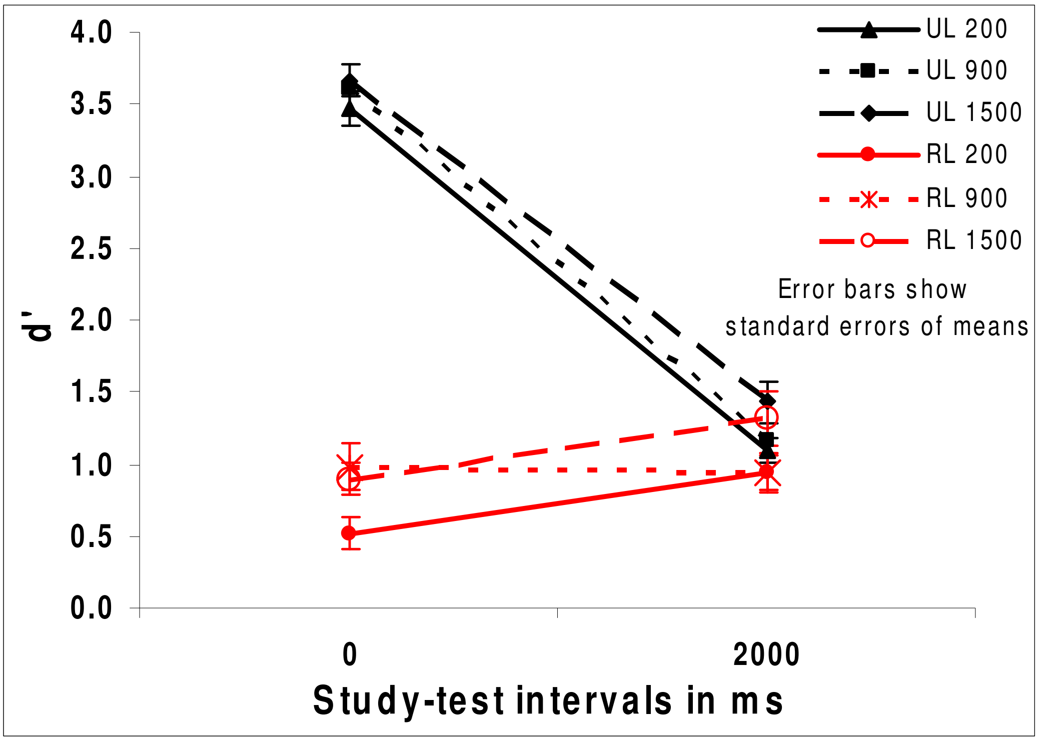
The first independent variable was location manipulated at two levels: unchanged vs. randomized locations. Participants were tested on two consecutive days at the same time of the day, half of them being tested with unchanged locations on the first day, and the other half being tested with randomized locations on the first day. The second independent variable was the study-test interval between the initial and test display. The study-test intervals of 0 ms and 2000 ms were chosen as the two levels of this factor. The third independent variable was study-display durations. The three levels selected were 200 ms (the same as in earlier experiments), 900 ms, and 1500 ms. The combination of three study-display durations and two study-test intervals resulted in six experimental conditions, each of which was administered in three blocks each for the unchanged and randomized locations conditions. With 20 trials in each of the 36 blocks, each participant completed 720 trials for the whole experiment. Participants practiced 8 trials of each block type in each of the two experimental sessions, starting from the longest study-display duration of 1500 ms and the longest study-test interval of 2000 ms, and working gradually through all the blocks to the shortest one of 200 ms study-display duration and 0 ms study-test interval.

Results

Mean change detection performance calculated from d-primes for all experimental conditions is shown in Figure 8.3.

Figure 8.3

Mean performance for unchanged and randomized locations for each study-display duration and each study-test interval in Experiment 11



In the legend to this and subsequent graphs in this chapter, the letters UL and RL stand for unchanged locations and randomized locations, and the numbers refer to the study-display durations. The relevant statistical tables appear in Appendix E.

As found in previous experiments, detection of swaps in binding was significantly reduced when location of stimuli was randomized from initial to test display, $F(1,11)=726.058$, $MSE=.108$, $p<.001$, *partial* $\eta^2=.985$. The main effect of study-test intervals was also significant, $F(1,11)=115.429$, $MSE=.339$, $p<.001$, *partial* $\eta^2=.913$ indicating that memory for bindings was significantly different for the two study-test intervals chosen in this experiment, i.e., 0 ms and 2000 ms. There was a significant interaction between location and study-test intervals, $F(1,11)=214.424$, $MSE=0.289$, $p<.001$, *partial* $\eta^2=.951$. Randomizing locations significantly disrupted performance at 0 ms but not at 2000 ms.

The main effect for study-display durations was also significant, $F(2,22)=8.444$, $MSE=0.150$, $p<.002$, *partial* $\eta^2=.434$. Pairwise comparisons with Bonferroni adjustment showed that the main effect of study-display duration was driven only by a significant difference between the study-display durations of 200 ms and 1500 ms. Neither the interaction of study-display durations with unchanged/randomized locations, nor with study-test intervals, was significant. The three factor interaction among unchanged/randomized locations, study-test intervals, and study-display durations, was also not significant.

Planned comparisons using directional paired samples t tests showed significant differences between performance at 200 and 1500 ms at both 0 ms, $t(11) = 3.188$, $p<.005$, and 2000 ms, $t(11) = 2.080$, $p<.031$, for randomized locations, and for 2000 ms for unchanged locations $t(11) = 2.379$, $p<.018$. The difference between 200 ms and 900 ms was also significant at 0 ms for randomized locations, $t(11) = 2.623$, $p<.024$. With Bonferroni adjustment, however, only the difference between 200 and 1500 ms at the study-test interval of 0 ms for randomized locations, $t(11) = 3.188$, $p<.005$, remained significant. Inspection of Figure 8.2 confirms that increasing the study-display duration raises the performance level for randomized locations from 200 to 1500 ms for the study-test intervals of both 0 and 2000 ms. This happens for unchanged location as well at 2000 ms, but not at 0 ms. The latter is probably due to ceiling effects in the participants' performance, the average proportions for all three study-display durations converging near a d-prime of 3.5.

Comparing swaps

Additional analyses were done to test if the type of swap had any effect on the participants' performance in the randomized and the unchanged locations conditions. Neither the main effect for swaps, nor any of the interactions involving swaps were significant.

Discussion

In keeping with the expectation from previous literature (Barrouillet et al., 2004; Barrouillet & Camos, 2007; Liu & Jiang, 2005; Pashler, 1988) that increasing exposure would enhance performance, better swap detection occurs with longer study-display durations in randomized locations conditions at both study-test intervals, and also at 2000 ms unchanged locations. This effect is, however, not present for unchanged locations at 0 ms, probably because performance is at ceiling in that condition.

Nevertheless, there is no *differential* effect of increasing study-display duration from 200 to 1500 ms on performance at the two different study-test intervals. This is particularly clear in the randomized condition where the graph lines for the study-display durations of 200 ms and 1500 ms are parallel to each other. One may infer that increasing the study-display duration may increase performance in each condition, but it does nothing to the sheer amount of disruption experienced due to randomized locations. Thus the inhibition of irrelevant features is most likely a post-encoding process. Hommel (2005) suggested that the processing of an object results in feature binding such that when one feature is encountered again, the whole set is activated, and aids performance to the extent that the feature overlap is complete. Indeed, in his view relevance of features is a primary determinant of which features participate in binding in the initial encoding stage itself. However, this experiment shows that relevance of features assumes importance at the post encoding stage. This suggests that participants cannot inhibit features whilst the stimuli remain in view, probably because during encoding, all resources are devoted to remembering as many bindings of relevant features as possible in this task, which is beyond the capacity of VSTM. This is also in consonance with studies showing that brain areas pertaining to all features are initially activated whether the features are relevant or irrelevant (O'Craven et al.,1999a, 1999b; Schoenfeld et al., 2003; Winkler et al., 2005).

EXPERIMENT 12

Experiment 12 presented the stimuli one by one such that the study display was gradually built up. Each stimulus appeared after equal intervals, with a random selection of each stimulus to be presented. Other details remained the same as Experiment 11. The experiment was essentially designed to test the effect of providing an extra temporal code by sequential presentation of stimuli. This factor could enhance performance; or alternatively, disruption in configural encoding could decrease performance. In so far as the disruption of configural encoding was important, it was also expected that performance in the unchanged condition would decrease more than in the randomized condition, and hence the gap between the unchanged and randomized conditions would decrease, particularly at 0 ms, which was more affected by configural encoding than 2000 ms as per previous experiments.

Nevertheless, in comparison to presenting stimuli in a way that only one of them appears in the display at a time, by building up the display gradually, and allowing stimuli to remain on the screen as subsequent stimuli are presented, participants got the opportunity to use configural information regarding the relative location of each item in the display. If they use this information effectively, then this form of sequential presentation would have little, if any, effect on performance compared to Experiment 11.

Participants

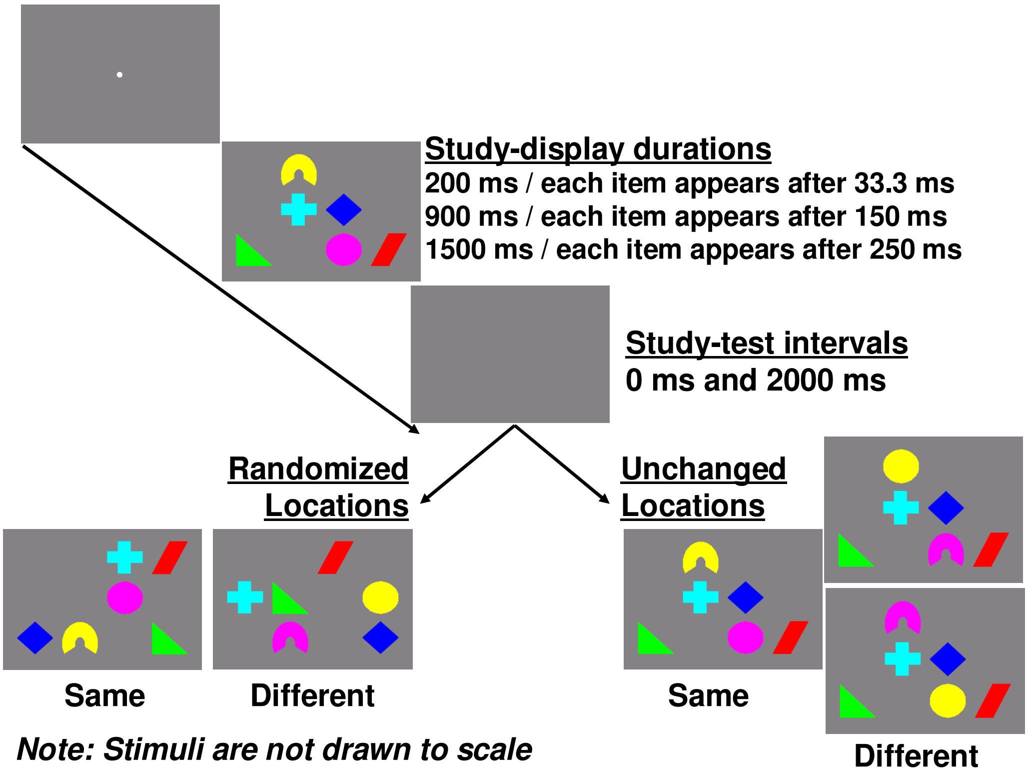
Twelve students (6 men and 6 women) in the age range 18-25 years were given an honorarium of £10 for their participation in the experiment.

Stimuli, Design, and Procedure

The stimuli were identical to Experiment 8, the only difference being that in this experiment the study-display involved sequential rather than simultaneous presentation of stimuli. The study display was ‘built up’ by presenting the six stimuli one by one at equal intervals as illustrated in Figure 8.1 in the introduction to this chapter. Each item was randomly allocated to each serial position without replacement. The design and procedure were the same as Experiment 8. Figure 8.4 illustrates the procedure.

Figure 8.4

Sequence of events in Experiment 12



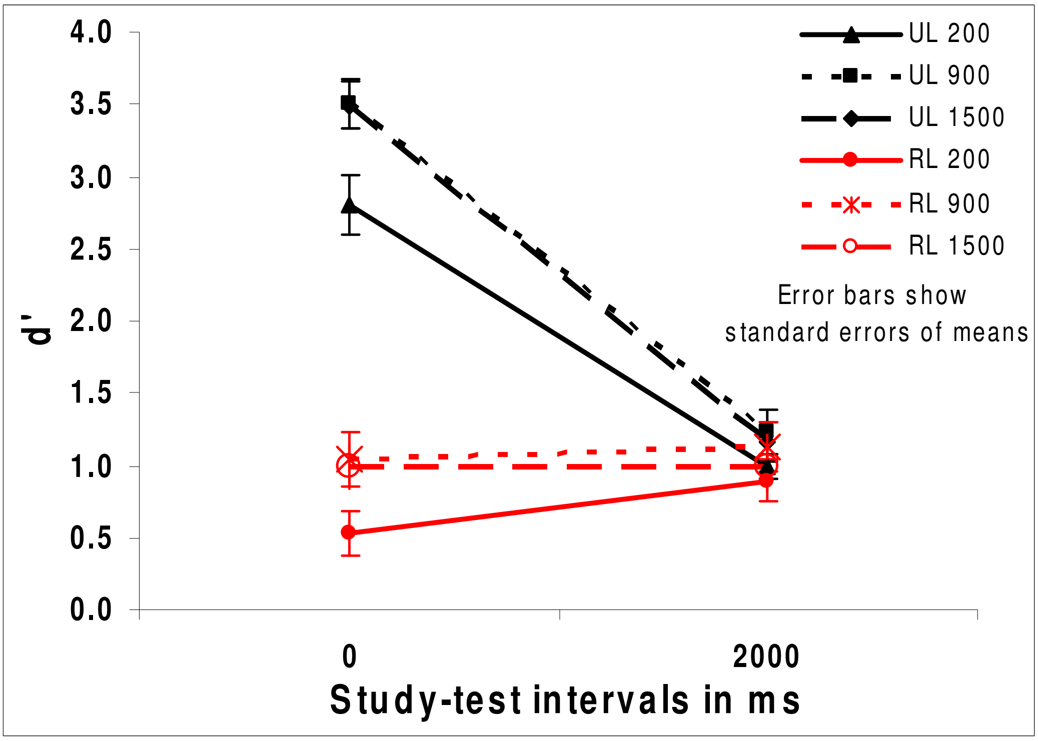
Note: Stimuli are not drawn to scale

Results

Mean change detection performance calculated from d-primes for all experimental conditions is shown in Figure 8.5.

Figure 8.5

Mean performance for unchanged and randomized locations for each study-display duration and each study-test interval in Experiment 12



Detection of change in bindings was significantly reduced when location of stimuli was randomized from study to test display, *F*(1,11)=101.460, *MSE*=0.566, *p*<.001, *partial* η^2=.902. The main effect of study-test intervals was also significant, *F*(1,11)=114.295, *MSE*=0.311, *p*<.001, *partial* η^2=.912 indicating that memory for bindings was significantly different for the two study-test intervals chosen in this experiment, i.e., 0 ms and 2000 ms. Analogous to previous experiments, there was a significant interaction between location and study-test intervals, *F*(1,11)=133.661, *MSE*=0..353, *p*<.001, *partial* η^2=.924. Randomizing location significantly disrupted performance at 0 ms but not at 2000 ms.

The main effect for study-display durations was also significant, *F*(2,22)=15.958, *MSE*=0.153, *p*<.001, *partial* η^2=.592. Pairwise comparisons with Bonferroni adjustment showed that the main effect of study-display durations was driven by a significant difference between the study-test interval of 200 ms and 900 ms, as well as 1500 ms, with no difference between the latter two. The interaction between study-display durations and study-test intervals was also significant, *F*(2,22)=3.978, *MSE*=0.168, *p*<.034, *partial* η^2=.266. The interaction of study-display duration with unchanged/randomized locations was not significant. The three factor interaction among unchanged/randomized locations, study-test intervals, and study-display durations, was also not significant.

Planned comparisons using directional paired samples t tests with Bonferroni adjustment, showed significant differences between performance with study-display durations of 200 and 900 ms, *t*(11) = 3.323, *p*<.004, and 200 and 1500 ms, *t*(11) = 3.411, *p*<.003, at the study-test interval of 0 ms for unchanged locations. Similarly for randomized locations, the differences were significant at a study-test interval of 0 ms, between study-display durations of 200 and 900 ms, *t*(11) = 5.513, *p*<.001, and 2000 and 1500 ms, *t*(11) = 3.880, *p*<.001. There were no significant differences in performance at 2000 ms. The lower performance with a study-display duration of 200 ms as compared to display durations of 900 and 1500 ms when tested immediately afterwards at 0 ms but not when tested after a study-test interval of 2000 ms precisely illustrates the significant interaction between study-test intervals and study-display durations. Inspection of Figure 8.5 confirms that increasing the study-display duration raises the performance level from 200 ms to 900 ms as well as 1500 ms with no difference between the latter two, especially for the study-test interval of 0 ms.

Comparing colour swaps and shape swaps

Additional analyses were done to test if the type of swap had any effect on the participants' performance. Both, in the randomized as well as unchanged locations conditions, neither the main effect for swaps, nor any of the interactions involving swaps were significant.

Serial position analyses

Sequential presentation of stimuli allowed an analysis of serial position effects. There were six stimuli, with 15 possible combinations of any two stimuli, which could swap on any trial. Despite that all these 15 possible combinations were not presented an equal number of times to all participants, as they were randomly determined over 8640 trials in the experiment, serial position effects were explored by calculating proportions of hits, and then converting these into d-primes.

One way analysis of d-primes based on all 15 possible swaps was significant $F(14,154)=2.300$, $MSE=0.101$, $p<.007$, *partial* $\eta^2=.173$, and Figure 8.6 illustrates the differences in d-prime scores for performance with the different combinations of swap stimuli. This data was also arranged for each stimulus position to clearly illustrate the serial position effects. These six figures appear together as Figure 8.7.

Figure 8.6

Serial position effects in Experiment 12

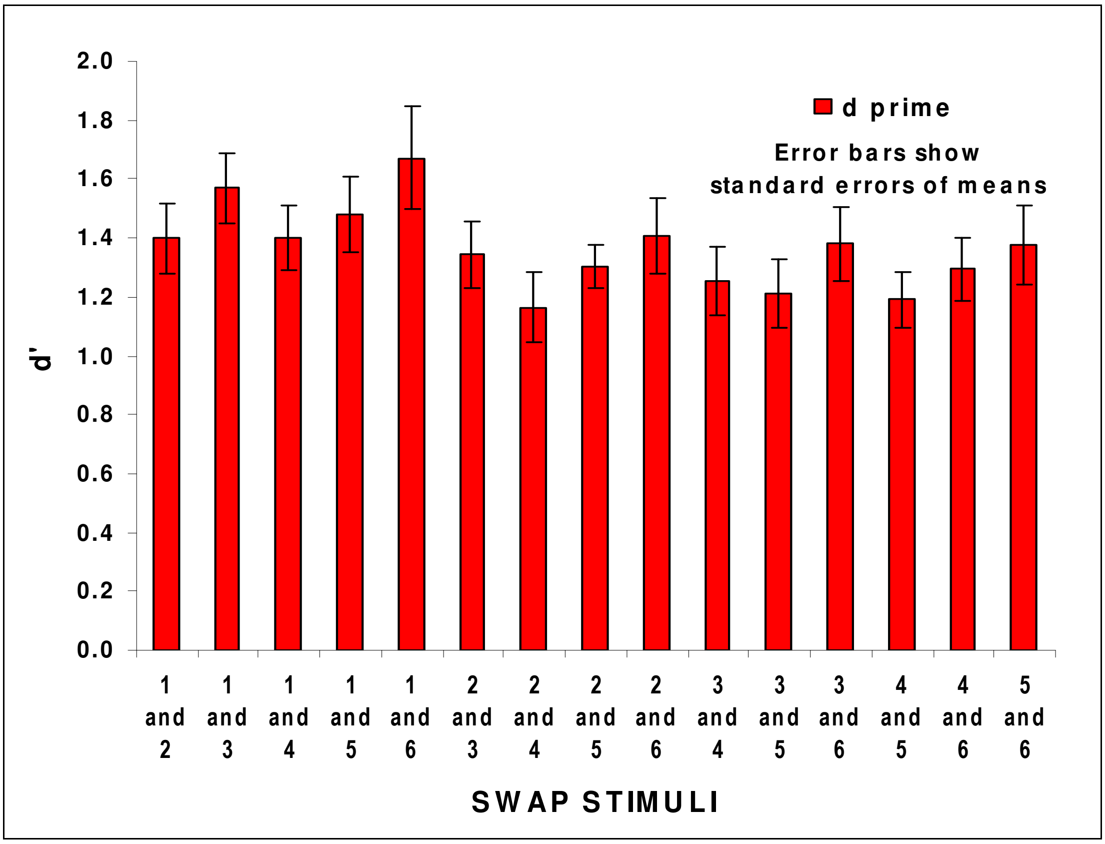
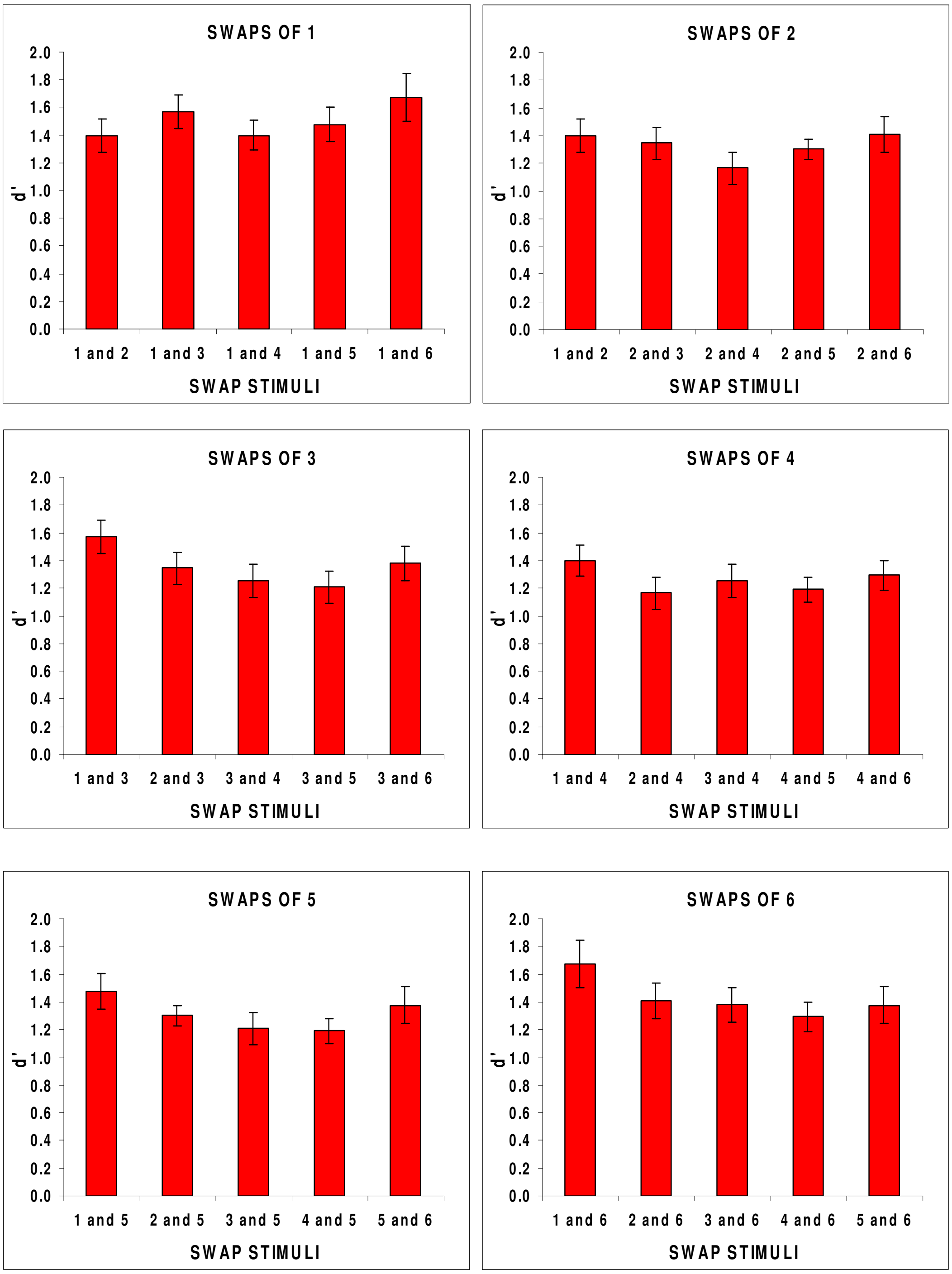


Figure 8.7

Serial position effects for each stimulus position in Experiment 12

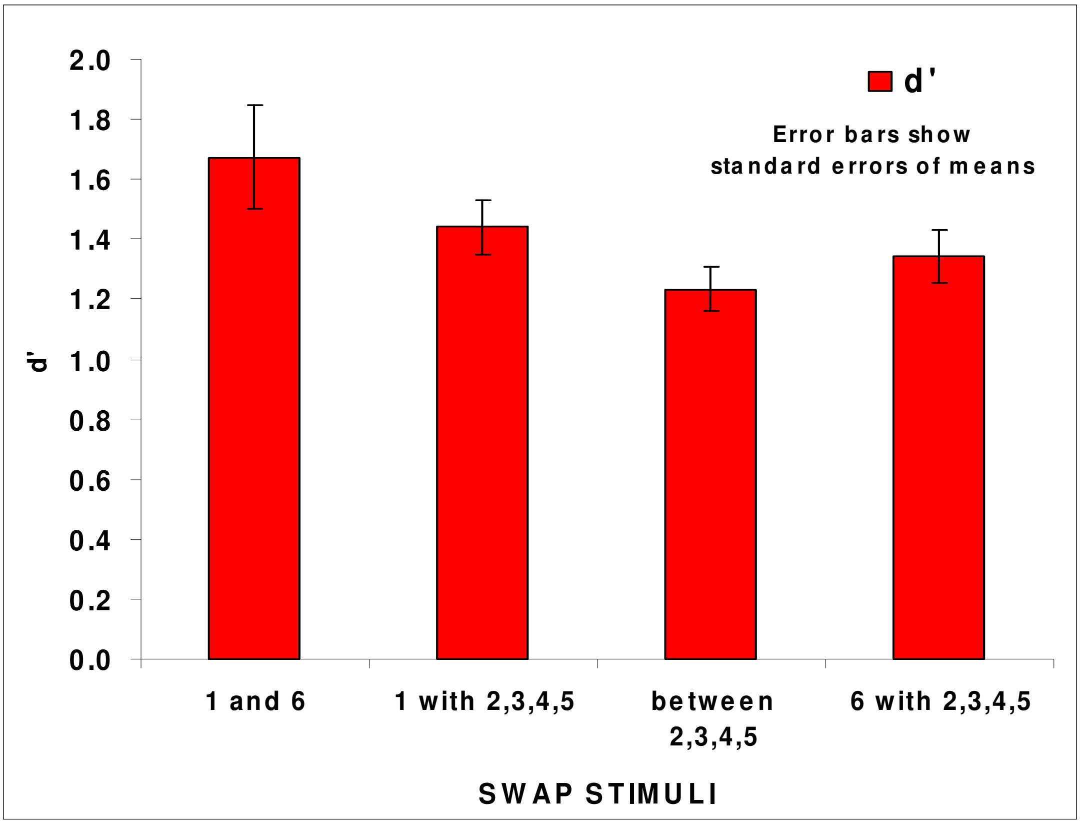
Error bars show standard errors of means



To conduct the serial position analyses, the many possible combinations, were combined into four categories – (A) swaps between 1 and 6, (B) 1 with 2,3,4,5, (C) between 2,3,4,5, and (D) 6 with 2,3,4,5. One way analysis for these four categories was also significant $F(1.735,19.081)=8.350$, $MSE=0.087$, $p<.001$, *partial* $\eta^2=.432$ with Greenhouse-Geisser correction applied. Pairwise comparisons with Bonferroni adjustment showed that C was significantly different from A, $t(11) = 3.896$, $p<.001$, and B, $t(11) = 3.692$, $p<.002$. Without Bonferroni adjustment, C was also different from D, $t(11) = 2.240$, $p<.023$. Figure 8.8 depicts these results.

Figure 8.8

Serial position effects in the four categories of swaps in Experiment 12

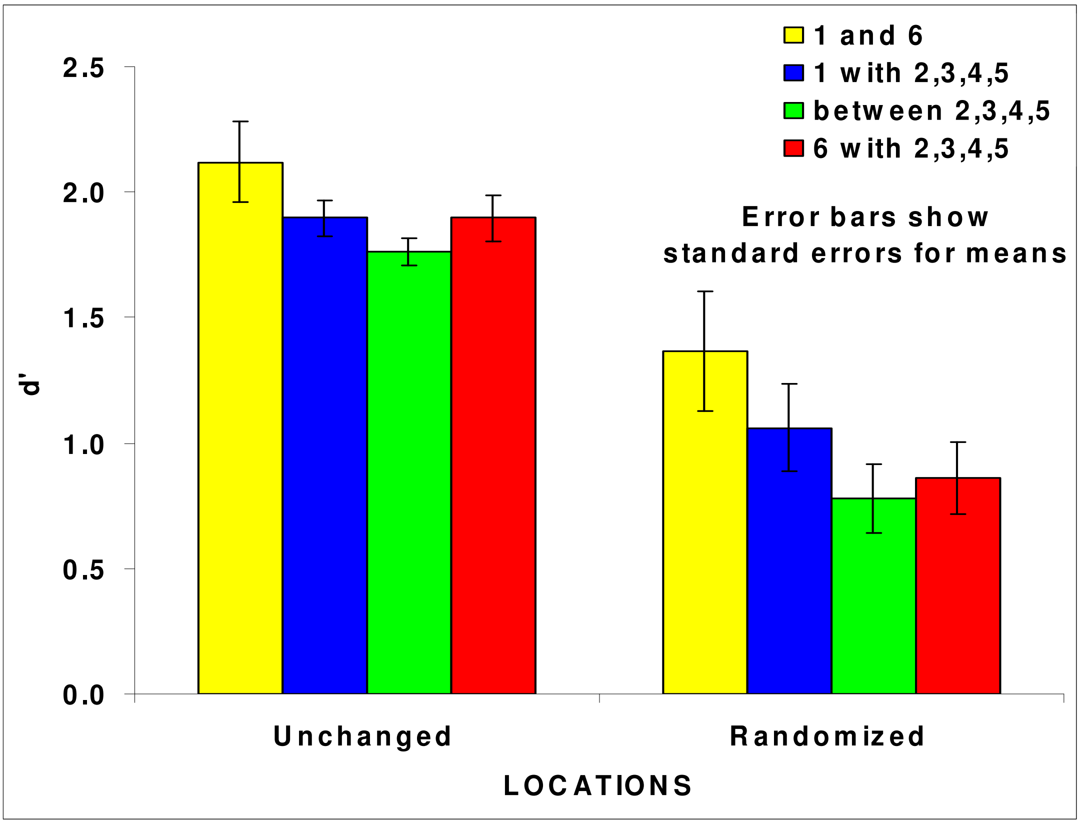


To explore whether the pattern of serial position effects varied with the three independent variables in this experiment, two way ANOVAs were conducted.

A repeated measures 2 × 4 ANOVA showed a reliable main effect of locations, $F(1,11)=39.004$, $MSE=0.502$, $p<.001$, *partial* $\eta^2=.780$, as well as swaps, *F*(3,33)=10.097, *MSE*=0.097, *p*<.001, *partial* η^2=.479, but the interaction between unchanged/randomized locations and swaps was not significant. The similar serial position effects obtained in unchanged and randomized locations conditions are clear in Figure 8.9.

Figure 8.9

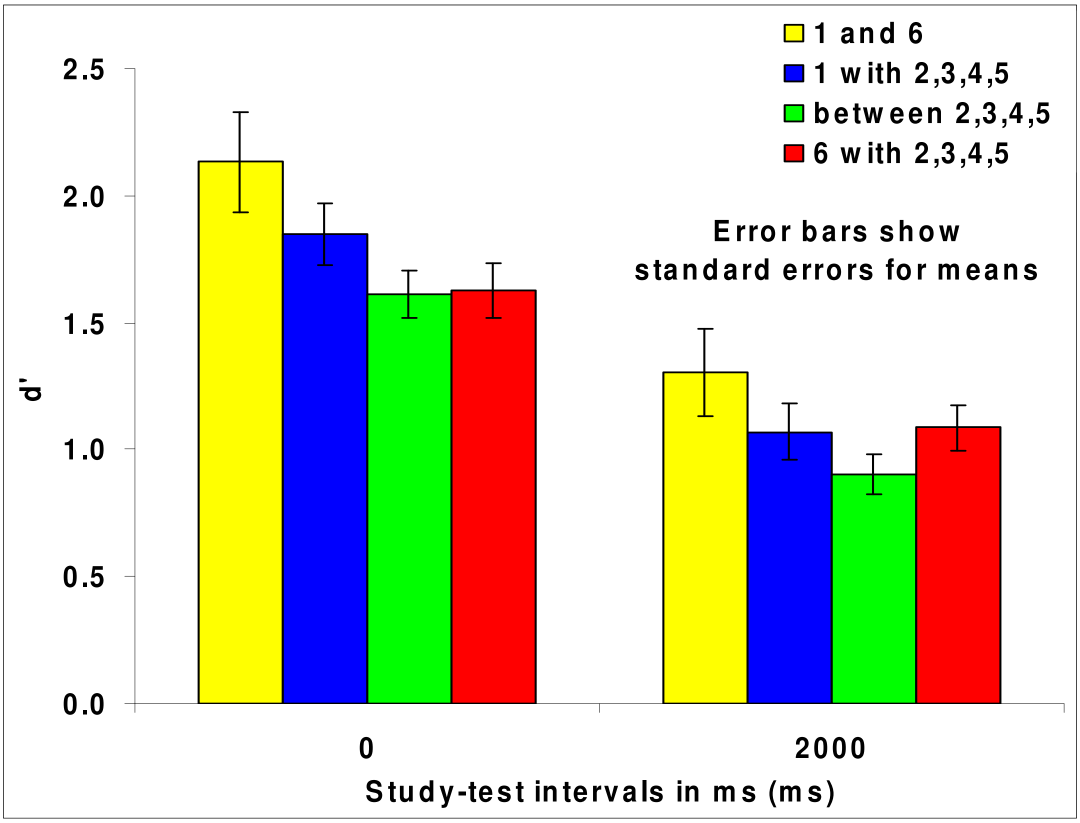
Serial position effects for unchanged and randomized locations in Experiment 12



A repeated measures 2×4ANOVA showed a reliable main effect of study-test intervals, *F*(1,11)=56.434, *MSE*=0.217, *p*<.001, *partial* η^2=.837, as well as swaps, *F*(3,33)=10.348, *MSE*=0.090, *p*<.001, *partial* η^2=.485, but the interaction was not significant. The similar serial position effects obtained at the two study-test intervals are clear in Figure 8.10.

Figure 8.10

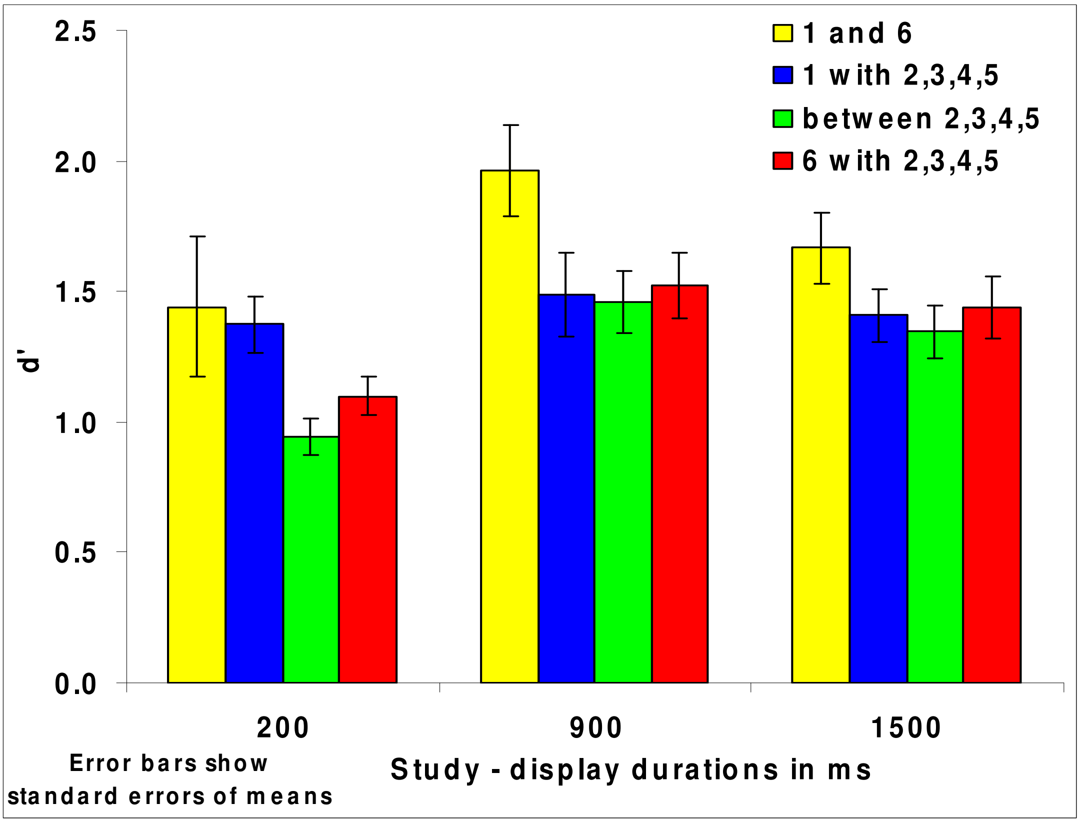
Serial position effects at study-test intervals of 0 and 2000 ms in Experiment 12



A repeated measures 3 × 4 ANOVA showed a reliable main effect of study-display durations, *F*(1,11)=12.546, *MSE*=0.152, *p*<.001, *partial* η^2=.533, as well as swaps, *F*(3,33)=10.816, *MSE*=0.118, *p*<.001, *partial* η^2=.496, but the interaction between the two was not significant. The similar serial position effects obtained at the three study-display durations are clear in Figure 8.11.

Figure 8.11

Serial position effects at study-display durations 200, 900 and 1500 ms in Experiment 12



The analysis to test the three-way interaction between these variables was not conducted because when further bifurcated, in each experimental condition, there was at least one participant who was not presented with at least one combination of swaps. Indeed, three values, which were other wise indeterminate, were substituted by an imaginary close value to enable the study of the interaction between swaps and study-display durations.

Discussion

This experiment also replicated the pattern found in earlier experiments in that performance was impaired by randomizing locations at 0 ms but not at 2000 ms. The experiment also resulted in a significant interaction between study-display durations and study-test intervals. The short duration of 200 ms resulted in poorer performance as compared with 900 ms as well as 1500 ms when tested immediately afterwards at 0 ms. A possible reason for this is that the faster rate of presentation in the 200 ms condition means that every 33.33 ms a new stimulus is presented in the display. Not only is each item encoded by itself, but also, it is to be encoded in relation to the other stimuli. This resource demanding process becomes even more difficult due to the limited time available in this condition, and hence performance is decreased. In contrast, 900 ms or 1500 ms allow respectively 150 and 250 ms per item, which is sufficient time to process each individual stimulus in itself, and in relation to other stimuli.

The serial position analyses showed that processing of sequentially presented stimuli does occur according to the serial positions. Overall, the primacy effect seems to be stronger in this experiment. Nevertheless, none of the three main independent variables had significant interactions with serial position, suggesting that serial position effects were immune to the differences in these variables. A more detailed discussion of serial position effects and of the comparison of this experiment with Experiments 11 and 13 is deferred until after the separate report of all experiments in this chapter.

EXPERIMENT 13

The motivation for Experiment 13 was similar to Experiment 12 in that stimuli were presented sequentially to disrupt configural encoding. This disruption was designed to be considerably more as compared to Experiment 12, because each previous stimulus vanished as the next one was presented, and the participant never saw the whole configuration together. It was expected that this disruption of configural encoding would reduce the gap between unchanged and randomized conditions at 0 ms, which was more affected by configural encoding than 2000 ms. Nevertheless, if performance followed Experiment 9 with an immediate mask (which also disrupted the effects of configural encoding, though at a later stage), it was expected that a small but significant difference would remain between the unchanged and randomized location conditions.

Participants

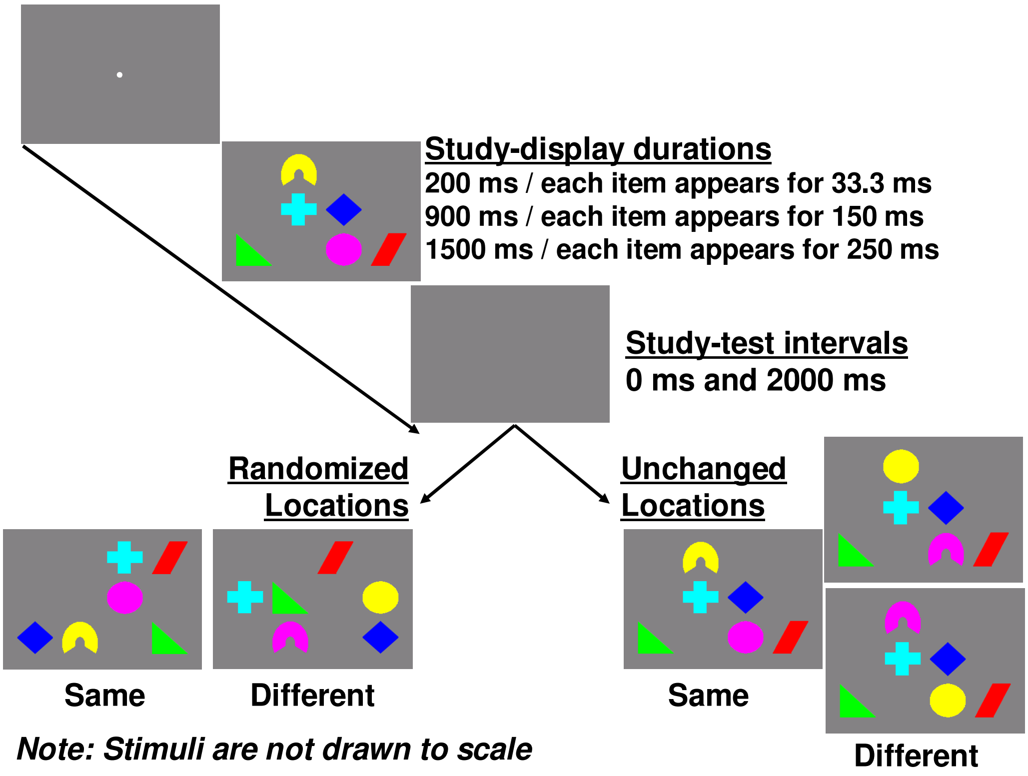
Twelve students (6 men and 6 women) in the age range 18-25 years were given an honorarium of £10 for their participation in the experiment.

Stimuli, Design, and Procedure

The sequence of events in Experiment 13 is shown in Figure 8.12.

Figure 8.12

Sequence of events in Experiment 13



Note: Stimuli are not drawn to scale

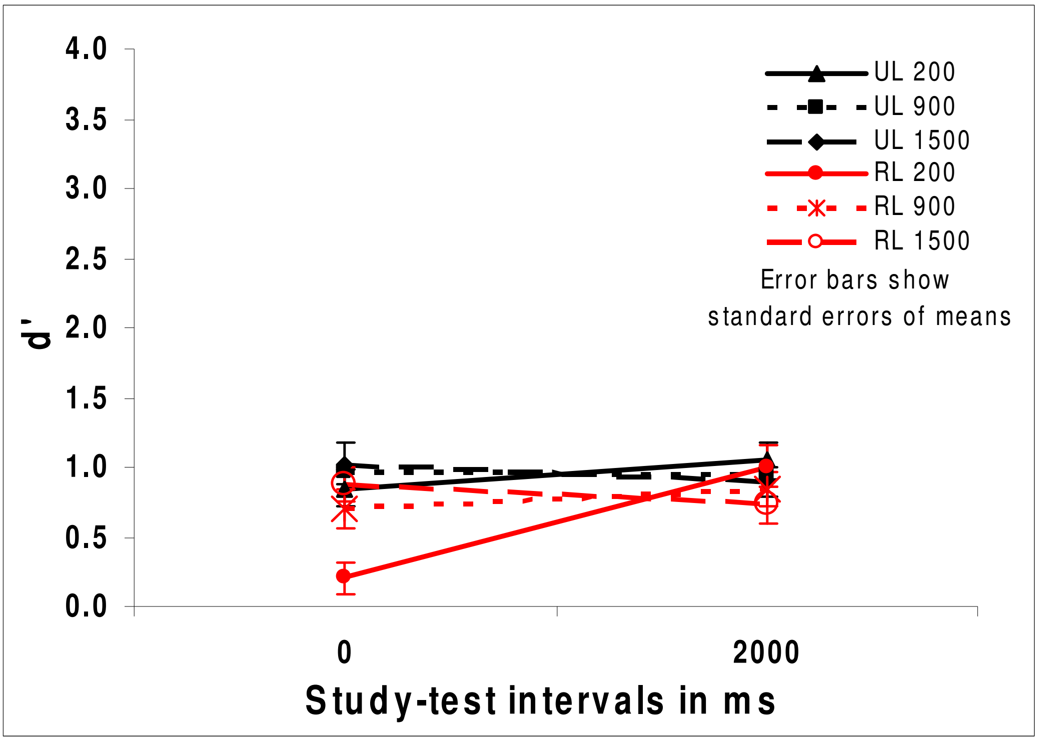
The apparatus and stimuli used were identical to Experiment 8 and 9, the only difference being that in this experiment the study display involved sequential presentation such that each stimulus vanished as the next was presented in the study display as illustrated in Figure 8.1 in the introduction to this chapter. Thus, all stimuli were never present together at any time. In a way, the task for the participants was to build up an image of the stimulus display in their mind. Each stimulus was randomly allocated to each serial position without replacement. Except for this change in the sequential presentation of stimuli, the design and procedure were the same as Experiments 11 and 12.

Results

Mean change detection performance calculated from d-primes for all experimental conditions is shown in Figure 8.13.

Figure 8.13

Mean performance for unchanged and randomized locations for each study-display duration and each study-test interval in Experiment 13



The main effect of unchanged/randomized locations was significant, *F*(1,11)=5.133, *MSE*=.365, *p*<.045, *partial* η^2=.318. The main effect of study-test interval was not significant. However, there was a significant interaction between location and study-test intervals, $F(1,11)=7.424$, $MSE=0.072$, $p<.020$, *partial* $\eta^2=.403$. Randomizing location significantly disrupted performance at 0 ms but not at 2000 ms.

The main effect for study-display durations was not significant, but the interaction between study-display durations and study-test intervals was significant, $F(1.205,13.253) =16.721$, $MSE=0.124$, $p<.001$, *partial* $\eta^2=.603$ with Greenhouse-Geisser correction applied. However, the interaction of study-display durations with randomized/unchanged locations was not significant. The three-factor interaction among randomized/unchanged locations, study-test intervals, and study-display durations, was also not significant.

Planned comparisons using directional paired samples t tests with Bonferroni adjustment, showed significant differences between performance with a study-display duration of 200 and 900 ms, $t(11) = 4.496$, $p<.001$, and 200 and 1500 ms, $t(11) = 5.833$, $p<.001$, at a study-test interval of 0 ms for randomized locations. In fact, post hoc comparisons with Bonferroni adjustment showed that the mean performance for randomized locations for the study-test interval of 0 ms with study-display duration of 200 ms was significantly different from all other means in the dataset.

Comparing colour swaps and shape swaps

Additional analyses to test if the type of swap had any effect on swap detection performance showed that neither the main effect for swaps, nor any of the interactions involving swaps were significant in the randomized as well as unchanged locations conditions.

Serial position analyses

Sequential presentation of stimuli allowed an analysis of serial position effects. There were six stimuli, with 15 possible combinations of any two stimuli that could swap on any trial. As for Experiment 12, despite that all these 15 possible combinations were not presented an equal number of times to all participants, as they were randomly determined for 8640 trials in the experiment, serial position effects were explored by calculating proportions of hits, and then converting these into d-primes.

One way analysis of d-primes based on all 15 possible swaps was significant *F*(14,154)=5.015, *MSE*=0.130, *p*<.001, *partial* η^2=.313, and Figure 8.14 illustrates the differences in d-prime scores for performance with the different combinations of swap stimuli. This data was also rearranged for each stimulus position to clearly illustrate the serial position effects. These six figures appear together as Figure 8.15.

Figure 8.14

Serial position effects in Experiment 13

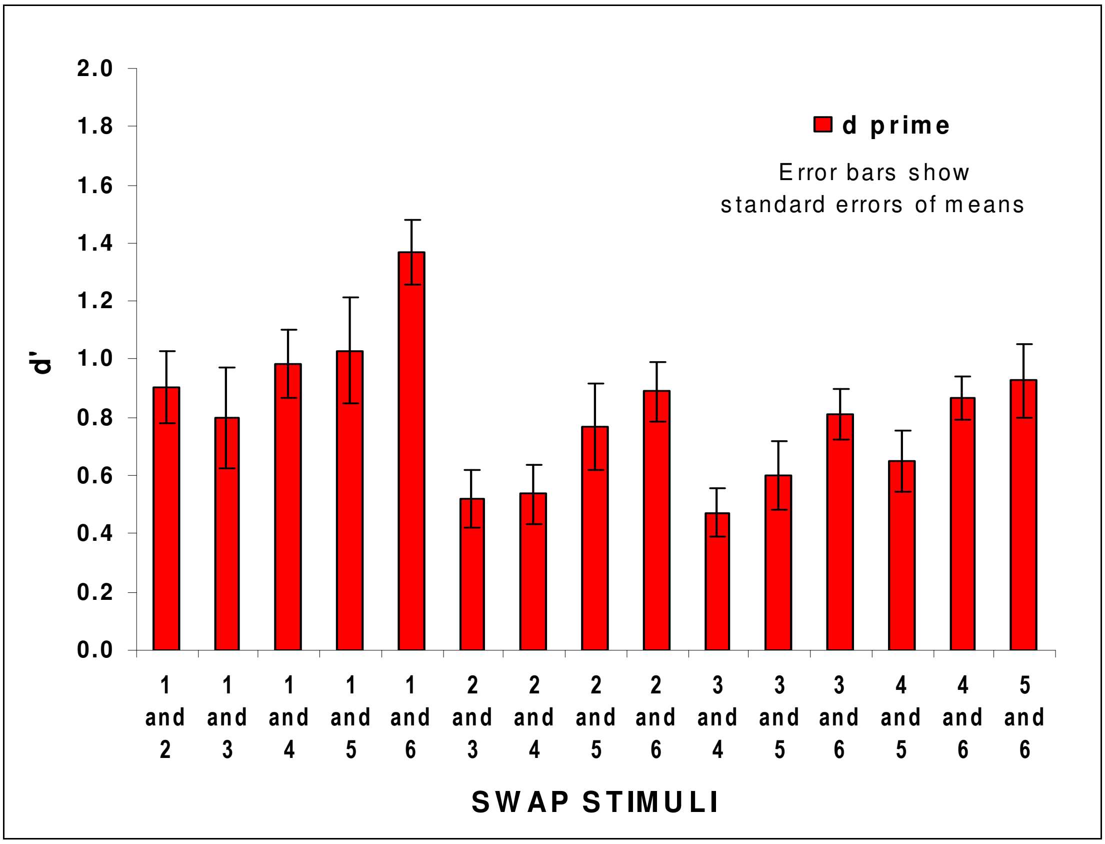
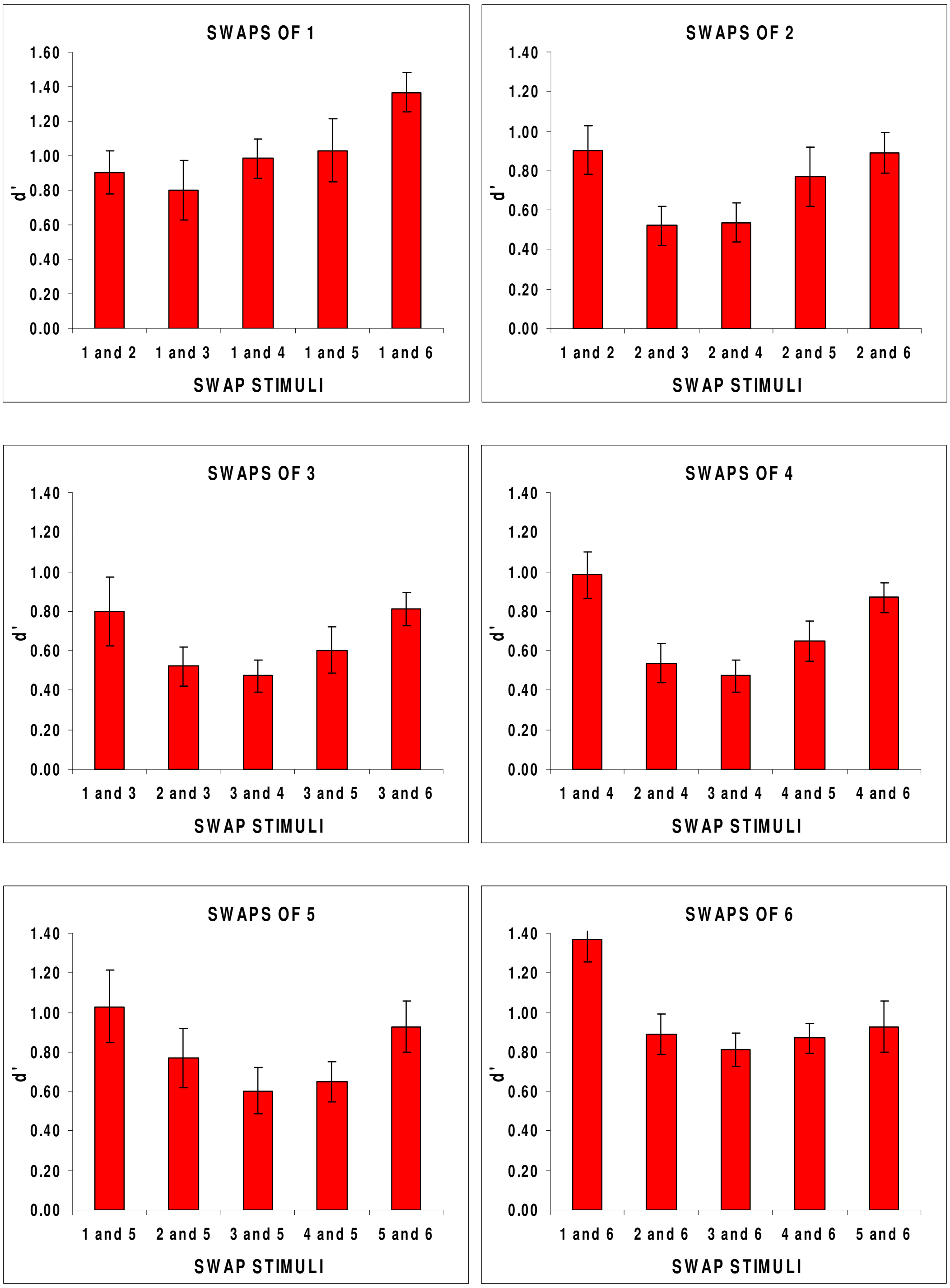


Figure 8.15

Serial position effects for each stimulus position in Experiment 13

Error bars show standard errors of means.



For further analyses, the many possible combinations were combined into four categories – (A) swaps between 1 and 6, (B) 1 with 2,3,4,5, (C) between 2,3,4,5, and (D) 6 with 2,3,4,5. One way analysis for these four categories was also significant *F*(3,33)=17.952, *MSE*=0.069, *p*<.001, *partial* η^2=.620. Pairwise comparisons with Bonferroni adjustment showed that C was significantly different from A, *t*(11) = 6.446, *p*<.001, and B, *t*(11) = 3.052, *p*<.011, and D, *t*(11) = 3.445, *p*<.005. Figure 8.16 illustrates these differences.

Figure 8.16

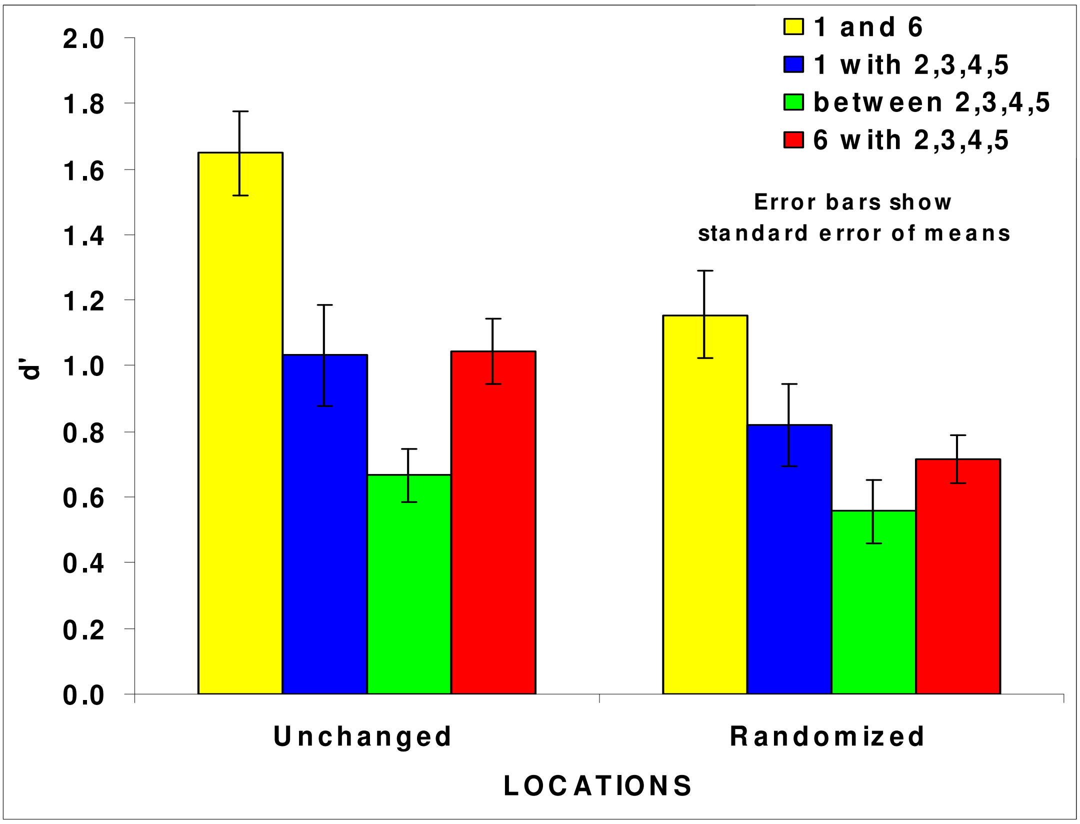
Serial position effects in the four categories of swaps in Experiment 13

To explore whether the pattern of serial position effects varied with the three independent variables in this experiment, two way ANOVAs were conducted.

A repeated measures 2×4 ANOVA testing the effects of unchanged/randomized locations and swaps showed a reliable main effect of locations, *F*(1,11)=10.185, *MSE*=0.193, *p*<.009, *partial* η^2=.481, as well as swaps, *F*(3,33)=19.215, *MSE*=0.135, *p*<.001, *partial* η^2=.636, but the interaction between unchanged/randomized locations and swaps was not significant. The similar serial position effects obtained in unchanged and randomized locations conditions are clear in Figure 8.17.

Figure 8.17

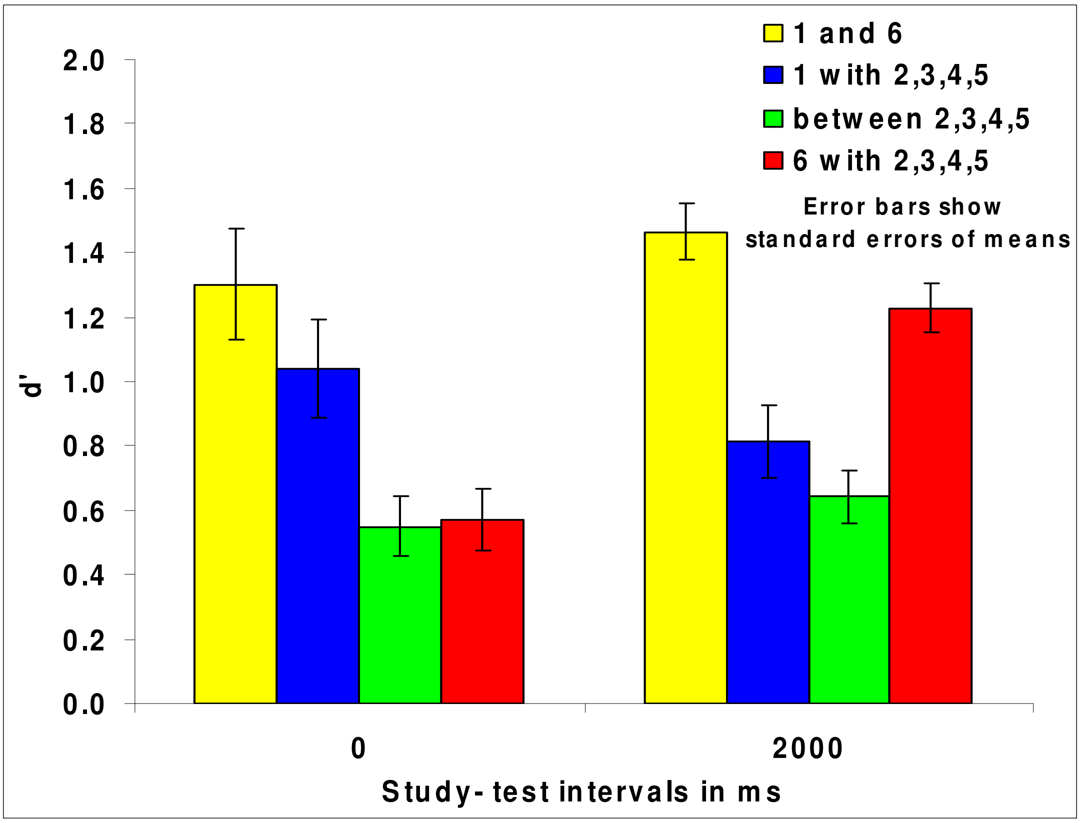
Serial position effects for unchanged and randomized locations in Experiment 13



A repeated measures 2 × 4 ANOVA testing the effects of study-test intervals and swaps showed no reliable main effect of study-test intervals (*F*<1), but significant main effect of swaps, *F*(3,33)=22.471, *MSE*=0.157, *p*<.001, *partial* η^2=.671, as well as a significant interaction between study-test intervals and swaps *F*(3,33)=5.229, *MSE*=0.036, *p*<.005 *partial* η^2=.322. The significant interaction is clear in Figure 8.18, showing a primacy effect at 0 ms, but a recency effect at 2000 ms.

Figure 8.18

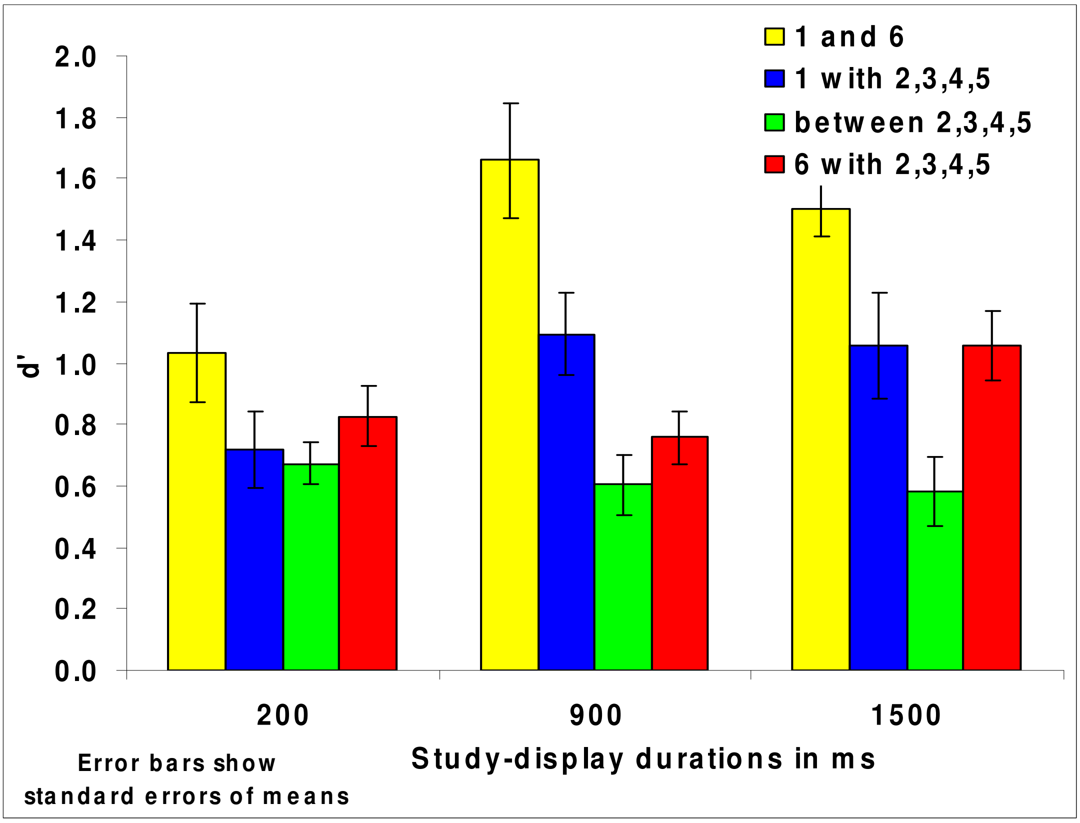
Serial position effects at study-test intervals of 0 and 2000 ms in Experiment 13



A repeated measures 3 × 4 ANOVA testing the effects of study-display durations and swaps showed a reliable main effect of study-display durations, $F(1,11)=3.638$, $MSE=0.205$, $p<.043$, *partial* $\eta^2=.249$, as well as swaps, $F(3,33)=16.914$, $MSE=0.236$, $p<.001$, *partial* $\eta^2=.606$. The interaction between study-display durations and swaps was also significant, $F(3,33)=3.230$, $MSE=0.132$, $p<.008$, *partial* $\eta^2=.227$. The different pattern of serial position effects for the three study-test intervals is shown in Figure 8.19.

Figure 8.19

Serial position effects at study-display durations 200, 900 and 1500 ms in Experiment 13



The analysis to test the three-way interaction between these variables was not conducted because when further bifurcated, in each experimental condition, there was at least one participant who was not presented with at least one combination of swaps. Indeed, values which were otherwise indeterminate, were substituted as missing values to study the interaction of swaps with study-test intervals (two values substituted) as well as with study-display durations (three values substituted). To ameliorate this limitation, Experiment 14 was done.

Discussion

This experiment is another demonstration of the role of iconic memory in the performance of the participants. Since the participant could only imagine the study display and never experienced all the stimuli together, configural encoding was precluded to a much greater extent than in Experiments 11 and 12. Performance in the unchanged locations condition at 0 ms deteriorates to a very large extent. However, the small difference between unchanged and randomized locations still emerges to be significant, substantiating the results of Experiment 9 with the immediate mask, where also this difference was reliable. As noted earlier, sequential presentation might disrupt the explicit configural information in the display, but participants might still attempt to create a mental representation of that configural information in VWM. This mental representation might confer some advantage on the unchanged condition because there is some information in VWM that matches the test display. In Experiment 9, an icon was initially available from the simultaneous display but then the contents of the icon were wiped by the mask. In the current experiment, the sequential presentation prevents the icon being formed in the first place, so again the icon cannot support performance. The difference between unchanged and randomized conditions occurs because there is some information in VWM that matches the test display in the unchanged locations condition or mismatches it in the randomized locations condition. Another notable fact in this experiment is the significantly poorer performance in the randomized locations condition at the study-test interval of 0 ms, with 200 ms study-display duration.

Clear serial position effects were shown in this experiment, with the data showing both primacy and recency effects. Study-test intervals as well as study-display durations interacted with swaps to change the pattern observed for the serial position effects. However, higher order interactions could not be statistically analyzed. This became one of the major reasons for designing Experiment 14.

EXPERIMENT 14

In both the experiments for sequential presentation, serial position effects were obtained with different levels of clarity when the analyses were conducted according to the serial position of the stimuli that were swapped on each trial. Nevertheless, the limitation to these results was that the analyses were post hoc and the swaps occurred randomly. Thus, some participants were not tested with some of the swaps in some of the experimental conditions. For example, participant 1 might not be tested with a swap between stimuli 3 and 4 in the experimental condition where study-test interval was 2000 and study-display duration was 200, participant 2 might not be tested with a swap between 5 and 6 in another experimental condition, and so on. Though this happened for different swap stimuli in different conditions with different participants, it was decided to overcome this limitation by designing a new experiment, which ensured that each swap was presented an equal number of times to all participants in all conditions.

To simplify the experimental design, the experiment was carried out only for the randomized locations condition, as the unchanged/ randomized locations had no significant interaction with the serial position effects in Experiment 12 as well as 13. Further, the randomized condition was chosen because it is the condition that is unaffected by the use of iconic memory, and therefore should offer an experiment that is focused primarily on VWM. Experiment 14 thus allowed the examination of the effects of study-test intervals and study-display durations on the serial position effects obtained in Experiments 12 and 13. Following the pattern of results in Experiment 13, it was predicted that these variables would have a significant interaction with swaps, and thus affect the primacy and recency effects obtained in the data. The three factor interaction was also of interest.

Participants

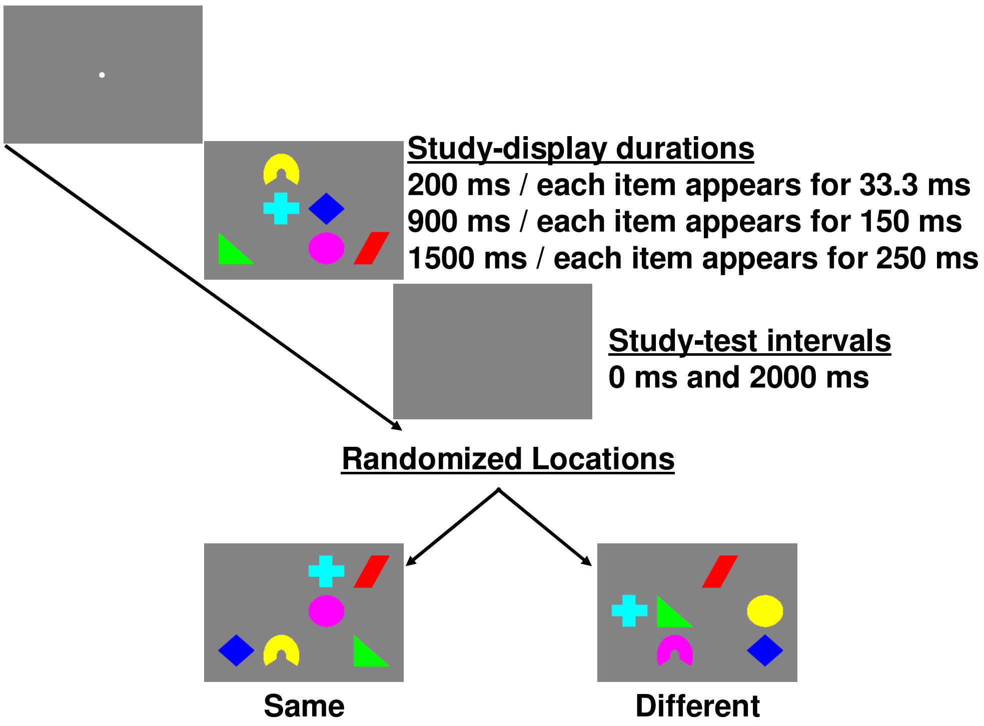
Twelve students (6 men and 6 women) in the age range 18-25 years were given an honorarium of £10 for their participation in the experiment.

Stimuli, Design, and Procedure

The stimuli were identical to Experiment 13, the study display involving sequential presentation such that each stimulus vanished as the next was presented. The experiment was designed a replication of the randomized location condition of Experiment 13. Figure 8.20 illustrates the procedure.

Figure 8.20

Sequence of events in Experiment 14



Note: Stimuli are not drawn to scale

The three independent variables were study-display durations (200, 900, and 1500 ms), study-test intervals (0 and 2000 ms), and swaps (all 15 possible combinations used for experimental design, grouped into four categories for analyses). Each participant was given 4 trials where there was a swap and thus experienced 360 ‘different’ trials, and 180 ‘same’ trials, all mixed randomly in a single session comprising 540 trials.

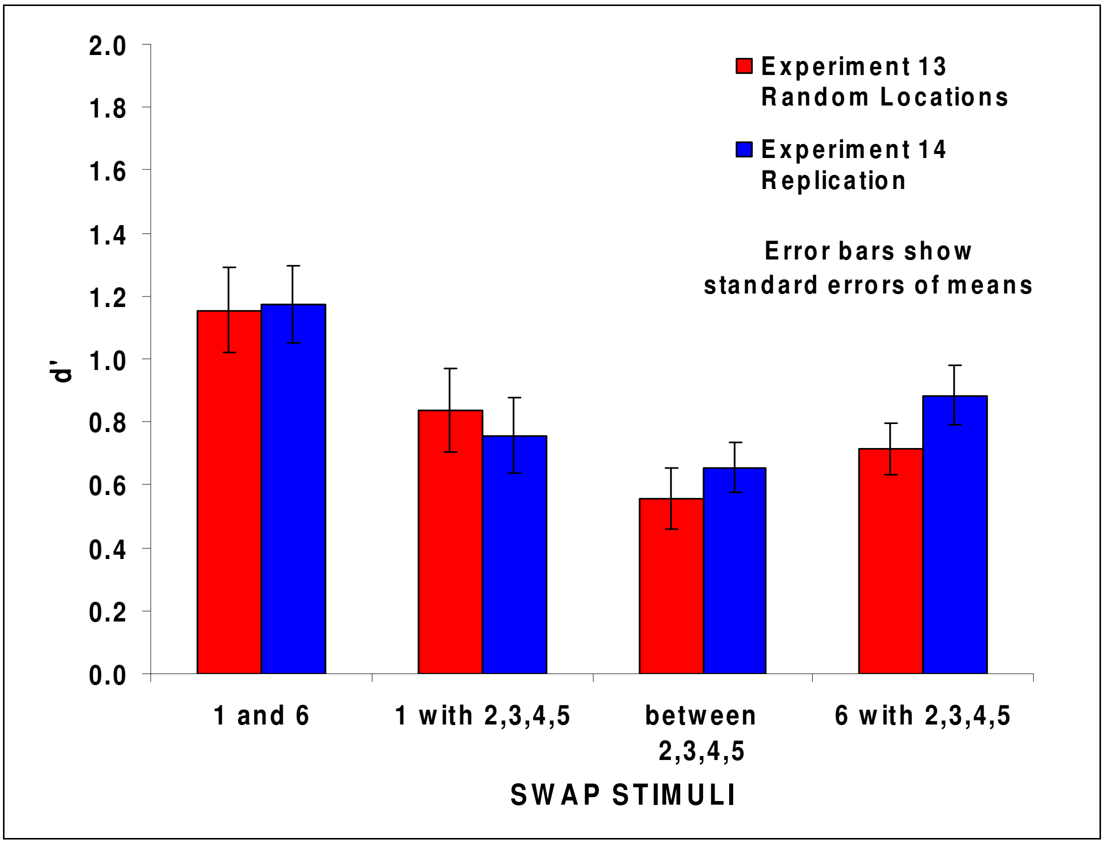
Results

Despite the small procedural differences, the results of this experiment almost duplicated the results obtained in the randomized location condition of Experiment 13 as illustrated by Figure 8.21. A 2×4 ANOVA testing the effects of experiments and swaps confirmed that although the main effect of swaps was significant, $F(3,66)=15.476$, $MSE=0.085$, $p<.001$, *partial* $\eta^2=.413$, neither the main effect of experiments nor the interaction between experiments and swaps was significant (both F<1).

Figure 8.21

Similarity of results of Experiment 14

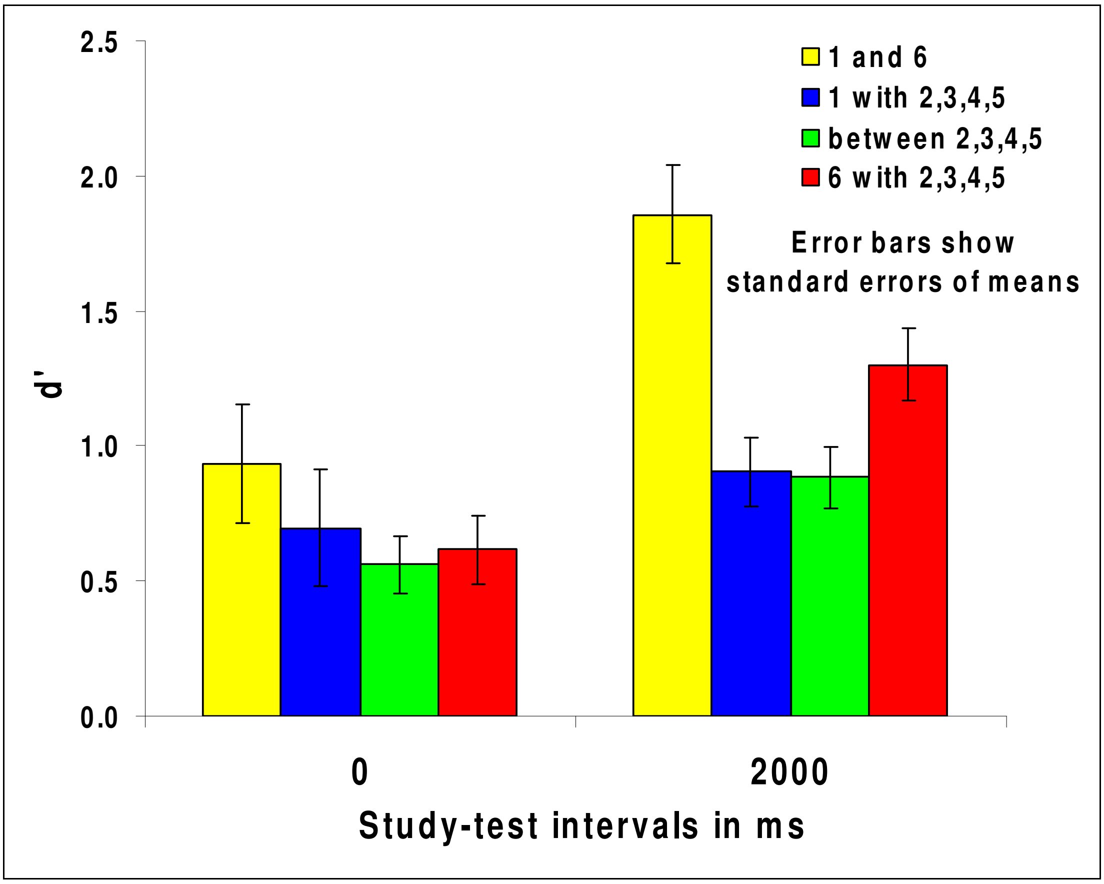
and Experiment 13 (randomized locations condition)



A repeated measures 2 (Study-test intervals) × 3 (Study-display durations) × 4 (Categories of swaps) ANOVA was used to analyze the results of Experiment 14. All the three main effects were significant. There was a reliable main effect of study-test intervals, $F(1,11)=13.367$, $MSE=1.538$, $p<.004$, *partial* $\eta^2=.549$, with better performance at 2000 than at 0 ms. There was a significant effect of study-display duration, $F(2,22)=3.715$, $MSE=0.795$, $p<.041$, *partial* $\eta^2=.252$, with the mean performance for 200 ms significantly lower in comparison to 900 and 1500 ms, with no difference between the latter as shown by paired comparisons using Bonferroni adjustment. There was a reliable difference in the four categories of swaps, $F(3,33)=9.347$, $MSE=0.700$, $p<.001$, *partial* $\eta^2=.459$. However, there was also a significant interaction between study-test intervals and swaps, $F(3,33)=4.782$, $MSE=0.406$, $p<.007$, *partial* $\eta^2=.303$. This is shown in Figure 8.22. No other effects were significant.

Figure 8.22

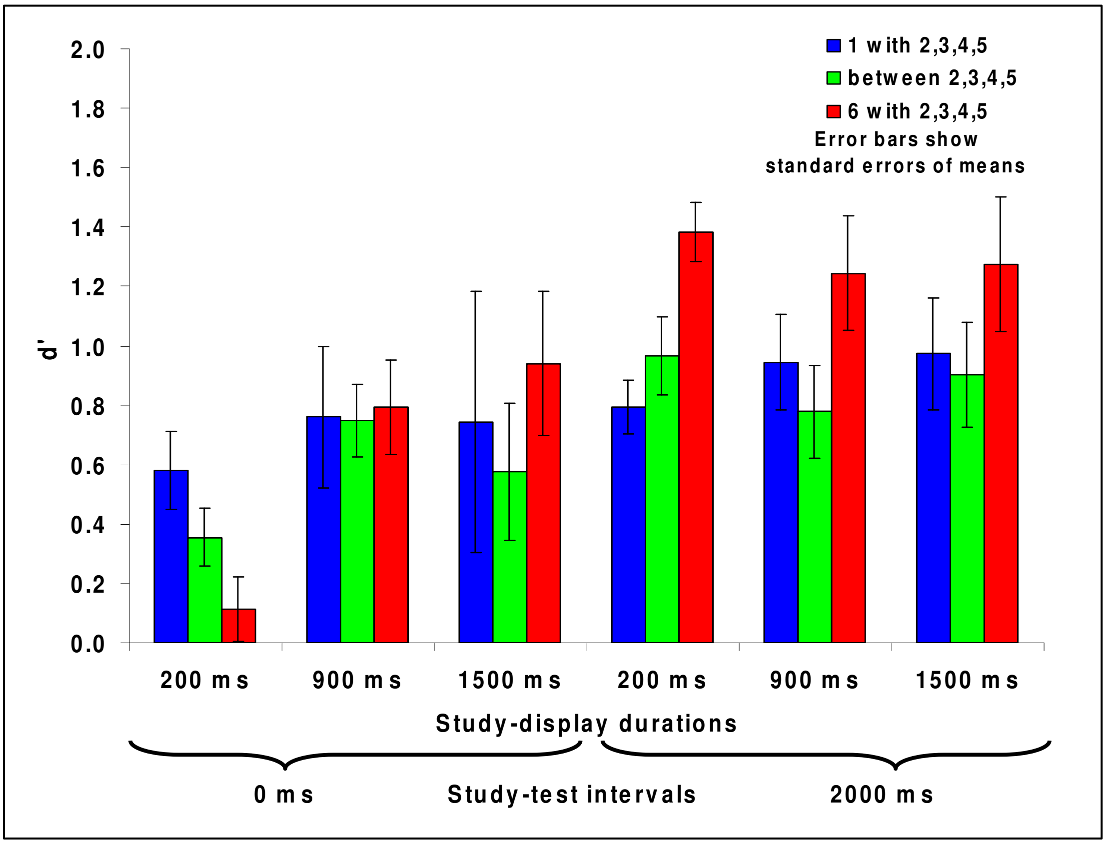
Interaction between study-test intervals and swaps



Since the primary motive for this experiment was to test the effects of study-display durations and study-test intervals on the serial position effects, a 2 (Study-test intervals) × 3 (Study-display duration) × 3 (Categories of swaps) repeated measures ANOVA was also done after excluding the data for swaps between 1 and 6, because that performance reflected both primacy and recency. Results showed a significant three factor interaction, $F(4,44)=2.718$, $MSE=0.163$, $p<.042$, *partial* $\eta^2=.198$, a reliable interaction between study-test intervals and swaps, *F*(2,22)=3.696, *MSE*=0.299, *p*<.041, *partial* η^2=.251, and a significant main effect of study-test intervals, *F*(1,11)=10.874, *MSE*=0.815, *p*<.007, *partial* η^2=.497. No other effects were significant. Figure 8.23 depicts the interaction.

Figure 8.23

Interaction: Study-display durations × Swaps × Study-test intervals



As is clear from Figure 8.23, the interaction denotes the different pattern of serial position effects with different study-display durations at the two study-test intervals. When the study-display duration was 1500 ms, at 0 as well as 2000 ms, both primacy and recency effects appear in the graph, though only the recency effect is significant at 2000 ms, *t*(11)=2.466, *p*<.015. When the study-display duration is 900 ms, no serial position effect is evident at 0 ms, but both primacy and recency appear in the graph at 2000 ms, though again, only the recency effect is significant, $t(11)=2.924$, $p<.007$. When the study-display duration is 200 ms, there is actually an interaction. At 0 ms, there is a significant primacy effect, $t(11)=1.943$, $p<.039$, with negative recency. However, at 2000 ms, there is a significant recency effect, $t(11)=4.930$, $p<.001$, with negative primacy shown in the graph.

The significance of primacy and recency effects in all cases was tested using directional paired samples t-tests. With Bonferroni adjustment, only the recency effect at 2000 ms with the study-display duration of 200 ms remained significant. This however, must be set against the fact that 18 means were tested through a lesser number of 12 selected planned comparisons specifically evaluating primacy and recency. These comparisons are protected by the significant interaction. Further, the experiment was a replication. These results are reported with the acknowledgement that the experiment lacks sufficient power, but the trend of results is clear and is interesting enough for future exploration.

To summarize the significant differences, the recency effect emerged clearly significant at 2000 ms for all study-display durations, whereas the primacy effect is significant only for the study-display duration of 200 ms when the study-test interval was 0 ms. Thus, the interaction between study-display durations and swaps is modulated by the effect of study-test intervals.

Discussion

Experiment 14 was conducted primarily to explore the effects of study-display duration and study-test intervals on primacy and recency effects. There was a general increase in performance from 0 to 2000 ms. The increase was primarily in recency. The decrease in primacy and increase in recency was most evident with the study-display duration of 200 ms.

The interesting result was that with a study-test interval of 0 ms, performance was less than what it was at 2000 ms. To speculate regarding the reasons for this result, at least three possible explanations may be considered.

The increase in performance at 2000 ms could be due to rehearsal, but the study-test interval of 2000 ms is rather short for explicit strategic rehearsal. Also, the increase is principally in recency, and it occurs in conjunction with a decrease in primacy from 0 to 2000 ms. If the participants were rehearsing, surely they would have rehearsed the initial few items which they remember at 0 ms. Rehearsal would have resulted in an increase or at least maintenance of primacy from 0 to 2000 ms. Further, if primacy was simply due to rehearsal, then the participant would be rehearsing the earlier items at the cost of the later ones, and no recency effect would have been obtained. However, the results show decrease in primacy, and increase in recency. As such, it is more likely that the primacy effect simply shows the effect of activation of representations, an activation that, nonetheless, reduces over time, and rehearsal is applicable only to the recency component, if at all.

Another explanation of the improvement in performance from 0 to 2000 ms is that it is evidence of inhibition. This implies that the substantial increase in recency from 0 to 2000 ms occurs because the last few items are encoded but inhibited at 0 ms. This inference would be consistent with the interpretation of results of previous experiments with simultaneous presentation at study display duration of 200 ms, which showed similar results.

Still another explanation of the lower performance at 0 ms could be that the test display interferes with the representation of the study display, reducing performance at 0 ms. This would be in line with the larger literature on the recency effect reviewed in Chapter 2, showing that it is abolished by even unrelated activity during the retention interval. However, these studies (e.g., Phillips and Christie, 1977) use paradigms such as recall, recognition, or reconstruction, and much longer retention intervals.

All of the above speculations are post hoc for this essentially exploratory experiment conducted merely to substantiate an interesting result. Clearly, much further research is required to disentangle these different explanations.

COMPARING EXPERIMENTS 11, 12, AND 13

A four way ANOVA was conducted to compare Experiments 11, 12, and 13 with experiments as the between subjects variable and unchanged/randomized locations, study-test intervals, and study-display durations, as within subjects measures.

There was a reliable main effect of Experiments, $F(2,33)=34.262$, $MSE=0.850$, $p<.001$, *partial* $\eta^2=.675$, with performance in Experiment 13 significantly lower than performance in Experiment 11 and 12, with no difference between the latter two.

Though the four factor interaction was not significant, the three way interaction between experiments, study-display durations, and study-test intervals was significant $F(4,66)=3.146$, $MSE=0.137$, $p<.020$, *partial* $\eta^2=.160$, as was the three way interaction between experiments, unchanged/randomized locations , and study-test intervals $F(2,33)=62.820$, $MSE=0.238$, $p<.001$, *partial* $\eta^2=.792$, indicating that in each case the factor of experiment modulated the significant two way interactions between the other two factors. The two way interactions of experiments with all the three other factors were also significant, with $F(2,33)=46.166$, $MSE=0.346$, $p<.001$, *partial* $\eta^2=.737$ with unchanged/randomized locations; $F(2,33)=56.261$, $MSE=0.289$, $p<.001$, *partial* $\eta^2=.773$ with study-test intervals; and $F(4,66)=3.044$, $MSE=0.156$, $p<.023$, *partial* $\eta^2=.156$ with study-display durations, indicating that the factor of experiments also modulated the significant main effects of these three factors.

A brief look again at Figures 8.3, 8.5, and 8.13 would clarify the differences between these experiments and enable a better grasp of results reported above. Performance is quite similar in Experiments 11 and 12, except that the interaction between study-test intervals and study-display durations is significant in Experiment 12 but not 11, with a lower performance in Experiment 12 in the unchanged locations condition at 0 ms with a study-display duration of 200 ms. The performance in Experiment 13 is completely different from Experiments 11 and 12, in that the gap between the unchanged and randomized location conditions is severely reduced, though not absolutely eliminated. Essentially, the difference between these two conditions in Experiment 13 is due to the significantly lower performance in the randomized locations condition at 0 ms, with the study-display duration of 200 ms. The performance in this condition replicates the performance in the same condition in the results of other previous experiments 1, 2, 5, and 8 reported in this thesis.

GENERAL DISCUSSION

Experiment 11 aimed to assess the effect of increasing the study-display duration on the interaction obtained in previous experiments. Though increasing the study-display duration from 200 to 900 and 1500 ms did result in a significant improvement in performance, it had no differential effect on performance at the two different study-test intervals. Consequently, it had no effect on the interaction between unchanged/randomized locations and study-test intervals. This allowed the conclusion that the inhibition of the disruption due to randomized locations and the lowering of performance that is evidenced in the randomized location condition at 0 ms is largely a post perceptual factor rather than an encoding factor. Not only is this supported by the host of studies suggesting that active inhibition is a higher order process that follows the initial registration of the stimulus (e.g. Braithwaite et al., 2007, Watson & Humphreys, 1998, 2005), it is also supported by the results reported in the previous chapter with the masking experiments.

Experiment 12 was designed to check whether sequential presentation aided performance by yielding an extra temporal code or alternatively, hampered performance by disrupting configural encoding. The results of the experiment almost replicated the results of Experiment 11. This might be because sequential presentation in this experiment gradually built up the study display, and was not sufficiently distinct from simultaneous presentation in terms of allowing configural encoding. Following the argument of Zimmer, Speiser, and Seidler (2003), it is also possible that participants probably used sequential encoding even with simultaneous presentation because the stimuli exceed VWM capacity and they are anyway free to move their eyes and head, though for the study-display duration of 200ms, the possible amount of such movement would have been very limited.

Yet, despite the general similarity of the results of Experiments 11 and 12, the interaction between the study-display durations and study-test intervals is significant in Experiment 12, in contrast to the lack of significance of the same effect in Experiment 11. The only difference between the two experiments is simultaneous vs. sequential presentation of the study display. And this difference is one possible reason for the significant interaction in Experiment 12. The difference in the performance in the two experiments lies in the lower performance in the unchanged location condition at 0 ms with the study-display duration of 200 ms in Experiment 12. Each stimulus was presented after 33.3 ms in this condition, and it is quite likely that this duration was simply insufficient for encoding the stimulus in itself as well as updating the configural representation in memory. Updating being resource demanding, resulted in lower performance. The time based resource sharing model of WM (Barrouillet et al., 2004; Barrouillet & Camos, 2007) suggests that lack of time makes any task more resource demanding. With more time in the conditions presenting each stimulus after 150 and 250 ms, the available resources could be easily allocated for updating the configuration. Overall, this result supports the argument that performance with sequential presentation can be maintained at levels equivalent to simultaneous presentation only by devoting more resources to it, and when these resources are taxed, performance with sequential presentation suffers.

Experiment 13 showed the maximum disruption in performance due to sequential presentation which precluded direct configural encoding from the display by presenting stimuli such that the previous stimulus vanished as the next one appeared. This allowed the participants to conjure up the pattern only in their imagination, if at all. The reliance on iconic memory, which aided performance at the short study-test intervals in the unchanged locations condition in other experiments, was markedly reduced, resulting in a severe disruption of performance. Nevertheless, reflecting the results of the Experiment 9 with immediate masks, a small but significant difference still remained between the unchanged and the randomized locations conditions at the study-test interval of 0 ms. This difference is due to the representations retained in VWM which match the test display and hence lead to better performance in the unchanged condition compared with the performance arising from a mismatch with the test display in the randomized condition

The serial position analyses for the experiments with sequential presentation showed primacy as well as recency effects. Finding serial position effects at the early stage process of binding was surprising because of the following reasons: (a) Binding is normally considered to involve simultaneous processing and the assumption is that as one object is selected, others recede to the background and are eventually lost from the system (Duncan, 1980, 2006). This does not appear to be so from the present results. In fact, it appears that the process of binding utilizes the presence of other objects in the visual field. (b) The participants were not explicitly asked to remember sequential order. The fact that serial order still dictates performance suggests that it is a factor in the encoding of stimuli rather than something, which is relevant only to retrieval. (c) The change detection task with whole displays is akin to recognition. Bow shaped serial position effects are usually not found with recognition tasks. In fact, Avons (1998) has contended that the serial position effect is task dependent. Recognition tasks are presumed to test item memory rather than memory for serial order. Thus, to find both primacy and recency despite these constraints indicates the importance of serial order in the binding process.

The results of serial position analyses in Experiments 13 and 14, showing lower performance at 0 ms than at 2000 ms, may be construed to be consistent with the idea of inhibition, as this result in randomized location condition is a virtual replication of the result in this condition in earlier experiments with simultaneous presentation. This explanation would suggest that inhibition is more applicable to the last few stimuli than to the first few, for primacy is reduced but the recency effect appears with increasing study-display durations. Why this effect should be particularly prominent with the study-display duration of 200 ms remains to be explored.

Another explanation is in terms of rehearsal. Why participants should rehearse the last few items rather than the first few, which they tend to remember better at 0 ms as shown by the primacy effect at 0 ms, is however, a problem for this explanation.

Still another explanation seems more plausible when the larger literature regarding recency is considered (reviewed in Chapter 2). This suggests that the recency effect vanishes at 0 ms and appears at 2000 ms simply because of interference from the subsequent test display, an interference which is greater at 0 ms than at 2000 ms. This would be in line with earlier studies in the verbal (Glanzer & Cunitz, 1966) and visual domains (Phillips and Christie, 1977), showing that recency is abolished by a filled delay of even a few seconds irrespective of whether the material presented during the delay is similar or different to the material to be remembered. These studies, however, use study-display durations much longer than 200 ms and different paradigms to assess memory.

Clearly, much further research is needed to unravel the implications of these different explanations.

CHAPTER 9

THE PROCESS OF BINDING

The aim of the thesis was to explore the process of binding whereby different features such as location, shape, colour, and others, are linked together to form a coherent representation of the object, with a specific focus to study the top-down and bottom-up influences in this process. The swap detection paradigm offered a means to track this process and study the relative influence of these factors by increasing the interval between the study and test displays at regular intervals. The stimuli were reduced to three basic features, location, colour, and shape, with the binding between two of them being studied whilst the third was rendered irrelevant through randomization. The focus was to study how far performance would be disrupted when a feature was rendered irrelevant through randomization in comparison to a condition in which it was unchanged. If there were no differences between unchanged and randomized conditions, it would indicate that participants can remove the unwanted irrelevant features right from the outset in accordance with task instructions. Reduced performance in the randomized feature condition would suggest that all features automatically participate in the initial representation even if they are irrelevant to the task. If a convergence occurs over time, it would suggest that relevant features can be consolidated and irrelevant features can be inhibited only gradually through the control processes of VWM. Further, it was of interest to study what other factors and processes affected this basic process of binding.

THE IMPORTANCE OF BEING RELEVANT

The input from the external world goes to different areas in the brain. Acting like a prism, the brain diffracts the whole input to various areas, and the ‘binding problem’ is how this information is integrated again to result in coherent objects that serve as a basis for cognitive processing (see Brockmole & Franconeri, 2009, p.1). If top-down factors are important, only information relevant to the task goals should be retained. In the present experiments, task goals were defined by instructions to the participants to remember the binding of two features and ignore the third. They were aided in this process by the randomization of the third feature to render it irrelevant. Performance in the randomized feature condition was compared to when the feature was unchanged to study *whether and when* the feature could be deleted from the visual system.

It was expected that performance in detecting change in bindings would be reduced when a feature is randomized from study to test as compared to when it is unchanged, if the feature had an initial representation, despite that the instructions were to ignore the feature and it was rendered completely non-informative and irrelevant to performance. It was also expected that as the visual system consolidated the binding of relevant features, this irrelevant feature would be inhibited, leading to a convergence of performance at longer study-test intervals.

This expectation was confirmed for locations in Experiment 1 which showed a convergence of performance at a study-test interval of 1500 ms. Experiments 2, 5, and 8 found a similar gap at the short study-test intervals and a later convergence in performance at the longer study-test intervals irrespective of whether the trials for the different experimental conditions were presented as blocks or randomized. A similar pattern of interaction was also found when shapes were randomized to study colour-location binding, and when colours were randomized to study shape-location bindings. This not only suggests that the effect is very robust, but also attests to the overriding importance of top-down factors in binding irrespective of the features involved. All features are treated the same way in VWM. They are selectively consolidated if they are relevant, and removed from the mental representation if they are irrelevant.

Nonetheless, there is no denying the differential processing of features. In line with physiological studies (Aymoz & Viviani, 2004; Lamberts, 2002, Moutoussis & Zeki, 1997, Zeki et al., 1991) and psychophysical evidence (Magnussen, 2000; Magnussen

& Greenlee, 1997; Magnussen et al., 1996), differential processing of features was found. There is greater disruption of performance when locations are randomized than when shapes or colours are randomized, with the disruption due to randomization of colours being the least. In addition, the removal of locations from the initial representation takes a much longer time than the removal of shapes or colours.

The results of the additional analyses comparing the two types of swaps possible in the trials when a swap occurred, confirmed that there are differences among features and that location is special as compared to other features. In the unchanged condition, the analyses comparing these different types of swaps yielded information about the relative importance of the features that swap during the test trials. Detection of location swaps is consistently easier than the detection of either shape swaps or colour swaps and yields higher levels of performance. However, the difference between colour swaps and shape swaps is not consistently found across experiments, despite the fact that it was large and clear in Experiment 1. Nevertheless, the study-test intervals where this happened in Experiment 1 were 200 ms and 2800 ms. Those study-test intervals were not used in later experiments. This suggests that there is a possibility that features are retained in separate feature maps, before and after binding at around 1500 ms. In some measure, this too corroborates the notion that binding of relevant features is not instantaneous, and features converge in a coherent object only somewhere around 1500 ms, at least in the paradigm used in this research.

The differences among the three features studied, locations, shapes and colours, follow the differential perceptual processing of these features. Location swaps are easiest to detect and location is the most difficult feature to ignore. Colour swaps are the most difficult to detect initially, and colour is the easiest feature to ignore. The results for shape fall in-between these two. This is in consonance with researchers showing that locations are processed in the dorsal stream, which is relatively automatic and works on an earlier time scale than the ventral stream (Vecera & Palmer, 2006, Velichkovsky, 1982, 2007). Between shape and colour, differentiation of forms happens before the surface features are filled in (Cinel & Humphreys, 2006; Humphreys et al., 2000, Humphreys et al., 2009). To be speculative, the differential processing of features might happen with other features such as orientation, size, textures, etc., as well, though these were not tested in the present research.

Bartels and Zeki (2006) had shown that although different kinds of bindings were processed at different time scales, the order of processing times did not follow the order of processing of single features. In contrast, Kent and Lamberts (2006) and Lamberts and Kent (2008) noted how processing of features in memory is analogous to basic perceptual processing. But Lamberts and Kent (2008) noted these differences only when memory load exceeded capacity at six features appearing in two different objects. There were no differences among features when only three features in a single object were to be remembered. It is noteworthy that memory load exceeds capacity in the present experiments too. Perhaps load is the critical factor, which explains these inconsistent results in literature, and features are processed in a manner analogous to basic perceptual processing whenever load exceeds capacity. Certainly, this is what would be predicted by the load theory of selective attention and cognitive control (Lavie & De Fockert, 2005, 2006; Lavie et al., 2004), if it were to be applied to this issue, for it suggests that greater WM load leads to more interference by distracters, implying that perceptual factors dominate when WM is loaded beyond capacity.

The differences in the amount of disruption experienced by the participants in the three experiments at 0 ms, imitate the importance of the ‘to be ignored’ feature in our daily lives. The disruptive effect is least when colour is the feature to be ignored, with a greater amount of disruption when shape is to be ignored, and the maximum disruption when location is to be ignored. The correct perception of the location of objects in space has survival value in our daily navigation of the world, and reflecting that importance, randomizing location disrupts performance to the greatest extent in these experiments.

The results support Treisman and Zhang (2006) as far as they demonstrated the reduced importance of location as a cue in binding at longer study-test intervals.

Similar to their results, using equidistant study-test intervals up to 2500 ms, the present experiments show that there comes a time, when location is no longer important as a cue for bindings in VWM. Our results, however, go against the overwhelming importance accorded to locations by Treisman in general. Perception may be location based, but memory may be not only location based, it might well be object-based, and also feature-based. Just as it is possible to ignore other features, it is possible to ignore locations too. It is only more difficult, not impossible. As compared to other features, location is special. But, in itself, it loses its importance in the binding process if it is not relevant. Thus relevance of features overrides the differential processing of features.

Duncan (1996, 1998, 2006) had suggested that all features, whether relevant or irrelevant, are activated, and as attention is focussed on an object, all features of the object are strengthened. Thus his concept of top-down biased selection, dictated by task relevance more than anything else, applies only at the level of objects and does not apply to features. He makes no prediction as to what happens as the representation is committed to memory. From the present results, however, it appears that encoding of features into VWM is also contingent on task relevance. As the representation is encoded into VWM for further manipulation, only the relevant features survive and the irrelevant ones are suppressed. This is, however, a gradual process, which also involves the differential processing of each feature. In a way, this extends Duncan’s concept of biased competition to features in VWM. Nevertheless, to be clear, in his view, binding is not a process. He assumes objects as the foundation of his theoretical edifice (Duncan, 2006). If anything, the suggestion is that binding happens due to conjunctively coded neurons.

In contrast, Humphreys (2001) has come to view binding as a process; and in fact, a process that can be further fractionated into the binding of forms, and thereafter, binding of surface features such as colour, to form. But his concern is mainly with features processed in the ventral stream, form and colour. The evidence cited is neuropsychological, based on patient population, and the use of TMS (Braet & Humphreys, 2009; Cinel & Humphreys, 2006; Humphreys et al., 2000; Humphreys et al., 2009).The fractionation of the binding process that is proposed on the basis of neuropsychological evidence and using TMS, is manifest here in the present research in behavioural experiments with normal healthy adults, thus generalizing the idea of differential processing of shape and colour. It also attests to the process of binding being one that is amenable to the relatively coarse behavioural assessment in experiments, and suggests the utility of the experimental paradigm in studying this process. It makes large scale studies using aspects of the experimental design to investigate individual or group differences in the binding process a feasible project, as well as correlational researches to study its relationship with other cognitive variables a distinct possibility.

Treisman (1998, 2006) also views binding as a process. She holds that there is a pre-attentive representation of features in separate feature maps, which are attached to the master map of locations as spatial attention is focussed on each location. Location and attention are thus both held to be essential for binding. Except for her emphasis on the importance of locations, she does not concern herself with the relevance of other features or any differentiation among them. The present results support her idea that location is special as compared to other features, viz., colour and shape. Nevertheless, just as locations are ignored if they are irrelevant, so are the other features. In this sense, location is not special. It is just another feature of the object that is dealt with the same way as are the other features by WM.

To be fair, Treisman and Zhang (2006) did report similar results as obtained in Experiments 1, 2, and 5 in this thesis. However, the motivation for their experiment was to assess whether features are available in separate feature maps even after being bound in object files. They did not interpret their findings in terms of relevance of features. Nevertheless, their results did show a convergence of performance over time when locations were held same or when stimuli moved to new locations, suggesting the reduced importance of locations over time in the detection of colour-shape bindings. The present research extends this finding to colours and shapes. Further, in an attempt to explain why the unique importance of any feature may be reduced over time, the experiments indicate that top-down processes, which organize basic information according to relevance, are of crucial importance.

The results are also in tandem with Woodman and Luck (2007) who have argued that the contents of VWM affect attentional selection during visual search, and strategic inhibition is possible in a visual search task, and that this can be taken as evidence of top-down processes affecting what is chosen to be perceived through attentional selection. This work is extended in the present thesis to show the time course over which top-down processes work, inhibit irrelevant features, and bind together relevant features.

Unlike researchers who insist that features, as represented in bottom-up processes, guide the process of search for objects (Muller & Krummenacher, 2006a, 2006b; but see Muller et al., 2009; Wolfe, 1994; Wolfe et al., 1989), or capture the vital resource of attention (Schreij et al., 2008; Theeuwes, 1992, 2004; Theeuwes et al., 2006), and thus may affect binding as a process, the present experiments show that the top-down factor of task relevance overrides the differences in the basic features involved in the process of binding. The results also contrast with Hommel (2004) who postulates the importance of task relevance as a factor at the time of initial binding. In the present results, it appears that the inhibition of irrelevant features occurs over time and is thus presumably a process within WM.

The account of the binding process that emerges is that features may not be bound together instantaneously and all at the same time. Instead, their processing in the visual system continues at different rates. This differential processing affects *when* they are bound in object representations. Object representations involving shape-location bindings are formed most easily or are the strongest, followed by colour-location bindings, followed by shape-colour bindings.

In the introductory chapter to the thesis, *whether, why*, and *how* some features were selected for binding over others were raised as fundamental questions about the binding process. From the experiments reported in this thesis, it is clear that there is a selective process that binds some features together. Further, the task relevance of features determines *whether or not* they are bound into the object representation, i.e., they are bound in the object weighted by their task relevance. Features are consolidated if relevant, and discarded if irrelevant. Certainly, there is no clear, coherent, strong object right from the outset. The next sections of this chapter discuss *how* this process of selection is implemented, and what other variables impact the process.

FOCUS ON ATTENTION

In all experiments, what is critical is that there is a convergence of performance between the unchanged and the randomized conditions as the study-test intervals increase. Time per se however, does not bring about this convergence. It merely allows other processes and variables to operate, and manifest their effects in the process of binding. In almost all experiments, the non-linear trends were also found to be significant. The significant non linear trends indicate that the development of the object from the initial stimulus representation is not a linear, gradual, monotonic increase with time, but there are other factors which affect the process of binding. One of these factors is the mechanism of attention.

Attention is not a singular entity; it has many facets and functions in a variety of ways in the process of binding. It is acknowledged that some researchers hold that bindings can happen without attention (Allen et al., 2006; Gajewski & Brockmole, 2006; Johnson et al., 2008; Mordkoff & Halterman, 2008). It is interesting to note that in such cases, the premise is that binding is the instantaneous strong integration of all features in the visual system, to be maintained or manipulated further in VWM. This substantially differs from the premise of this thesis that binding is a process that, over a period of time, results in a coherent meaningful object ready for further manipulation. Further, the experimental evidence is based on (a) equal amounts of attention required for detecting single features and bindings, which merely shows that detection of bindings is no more attention-demanding than single features, but does not allow the conclusion that binding happens in the complete absence of attention (b) maintenance of bindings over a period of generally around 900 ms after a 250 ms study display (e.g., Allen et al., 2006). The present experiments show that the process of encoding colour-shape bindings into VWM when locations are randomized is virtually over by 1500 ms, and much earlier for bindings involving locations. Thereafter, bindings are easily maintained up to 2500 ms. Other evidence (Mitroff & Alvarez, 2007; Treisman & Zhang, 2006) suggests that this maintenance is possible up until study-test intervals of 7-8 seconds. It is accepted that maintenance of bindings is not very attention demanding, but this cannot be taken to mean that attention is not required for the formation of bound objects, in the earlier process of binding which ends in coherent objects. This process is necessarily selective considering that the organism is faced with multitude stimuli and stimulus dimensions, all of which cannot possibly be bound together; and this selective process is resource demanding.

Certainly, the present experimental task, which not only presented stimuli beyond the four that are proposed to be the capacity limit of VWM (Cowan, 2001, 2009; Luck & Vogel, 1997; Zhang & Luck, 2008), but also required selection of relevant features over irrelevant ones, was designed to be attention demanding. In fact the experimental results go beyond showing that binding requires attention, to demonstrate how various kinds of attention are being used by the participants in the process of binding.

Comparisons between experiments with blocked and mixed presentation of trials were particularly instructive of the role of attention in the process of binding. The review of literature regarding blocked and mixed presentation had indicated that whereas blocked presentation enhanced the task focus, mixed presentation required extra resources for intra task as well as inter task processing. As such, though performance with mixed presentation is either similar or worse than blocked presentation when tested immediately, it results in superior memory when tested after an interval. This is known as the contextual interference effect (Lee & Magill, 1985; Li & Wright, 2000; Shea & Zimny, 1988; Wright et al., 1992).

Whilst Experiments 2, 3, and 4 used blocked presentation, Experiments 5, 6, and 7 used mixed presentation of study-test intervals. In line with the contextual interference effect, it was expected that mixed presentation would result in better performance at the longer than at the shorter study-test intervals. Results showed that mixed presentation led to improved performance at the longer study-test intervals in the experiments where shapes were to be ignored, and there was a trend towards better performance with mixed presentation at all study-test intervals when colours were to be ignored. However, when locations were to be ignored, an interaction was obtained with blocked presentation being no different from mixed presentation initially, but resulting in better performance at 2000 ms.

It was concluded that the increase in generalized attention, which was associated with mixed presentation, favoured the distributed spatial attention that was engaged in the experiments where colours and shapes were randomized, locations being fixed in these experiments. The participants were required to remember the bindings of colours or shapes with locations. All six stimuli occurred in fixed locations, so the task was essentially to maintain in memory, the configuration of the stimuli in terms of the colours or shapes. This is to say that the performance of the participants could have been aided by remembering which colours were where, or which shapes were where, in six fixed locations.

In contrast, object-focussed attention was presumably being used in the Experiments 2 and 5 where locations were rendered irrelevant. Even in the unchanged locations condition, the focus was on remembering colour-shape bindings with the six stimuli occurring in different random locations on each trial, and the instructions were to ignore locations. The task focus that accompanies blocked presentation favoured object based attention, but only at 2000 ms, presumably once the object had clearly evolved, the relevant features being consolidated and the irrelevant one deleted from the representation. Otherwise, no clear differences emerged between blocked and mixed presentation.

In Experiment 8, not only were the study-test intervals given in a mixed order, but the unchanged and randomized locations conditions were also randomly mixed, and the whole experiment was done in a single session. Comparing Experiments 2, 5, and 8, the three-way interaction between unchanged/randomized locations, study-test intervals, and experiments was significant. When further ANOVA was conducted separately in the unchanged and randomized locations conditions, and performance in Experiment 8 (all conditions mixed) was contrasted with Experiments 2 (blocked presentation) and 5 (mixed study-test intervals), no clear or consistent differences between the three types of presentation were discernible in the randomized locations condition, though the interaction was significant. However, for unchanged locations condition performance in Experiment 8 (all conditions mixed) was better at the longer study-test intervals and thus showed the contextual interference effect.

It was surmised that when all conditions were mixed for presentation in Experiment 8, the participants were prepared for the worst-case scenario of a randomized trial, and had to switch their mental set when an unchanged locations trial occurred. This set switching, utilized more WM resources, and thus resulted in the contextual interference effect being evident in performance. Lee and Magill (1985), and Li and Wright (2000) have explained the contextual interference effect by proposing that there is greater use of WM resources in the mixed condition because resources are required for both inter-trial and intra-trial processing. Switching task sets is among the three primary functions ascribed to the central executive (Baddeley, 2007) and it is well established that switching frequently is resource demanding (Monsell, 2003).

To summarise this section, it seems that the contextual interference effect appears in performance only when spatial attention is engaged and configural information can be used by the participants. In such conditions, mixed presentation yields better performance at longer study-test intervals, because the more intensive use of attentional resources probably aids the retention of configural information. When attention is object-based as in the randomized locations condition, the contextual interference effect is not observed, and there is no clear difference between mixed and blocked presentation. With regard to the features in the binding process, this suggests that binding involving locations would benefit from extra attentional resources, but binding of other features may not benefit from global, endogenous attention in the same way. The role of different types of attention in different kinds of feature-bindings is therefore, deserving of more focussed attention in future!

SPOTS OF TIME: THE MEMORY STORES

Experiments 8 – 14 helped to study the influence of different memory stores and processes in the process of binding. These experiments were conducted only for the feature of locations, because the previous experiments had already shown that although the different features were processed to different time scales, the pattern of performance was similar across features. In all cases, despite an initial disruption of performance due to randomization, there was a convergence at the longer study-test intervals, indicating that WM operated in the same way across features, consolidating relevant features and inhibiting the irrelevant ones.

One possible explanation of the results of Experiments 1-7 was that the superior performance in the unchanged condition was due to iconic memory of the study display. Though there was no denying that iconic memory had a role to play in performance, it was important to ascertain exactly to what extent it contributed to the difference in performance between the unchanged and randomized conditions. It was also important to assess the role it played in the randomized locations condition.

Since the classic experiments on iconic memory by Sperling (1960, 1963) masks have often been used to study iconic memory. Following these original experiments, many researchers assume that a mask completely obliterates the icon (e.g., Becker et al., 2000). Nevertheless, many others also recognized that some information is transferred out to VSTM almost as soon as the stimulus is presented and this information is relatively immune to the mask (Averbach & Coriell, 1961). Others too recognized informational persistence (Coltheart, 1980, Haber and Standing, 1969) and a few proposed that iconic memory had two components, an early retinotopic one and a later spatiotopic one (Breitmeyer et al., 1982; Feldman, 1985, McRae et al., 1987). In a recent study, Smithson and Mollon (2006) concluded that information in terms of higher-level features persisted despite a mask, and thus a mask did not really terminate the icon.

Thus, three experiments were designed. Experiment 8 provided the baseline performance without masks. In Experiment 9 an immediate mask was used to disrupt iconic memory, whereas in Experiment 10, a delayed mask was used to disrupt the central processes of consolidation and inhibition. Recognizing the confound between the type of mask and timing of a mask in the previous literature, a single type of mask with both perceptual and conceptual properties was designed and used in both experiments, so that differences between the performance in the two experiments could be attributed only to the timing of the mask.

It was found that the immediate mask presented for 100 ms severely disrupted performance in the unchanged locations condition. When presented after a delay of 300 ms, however, performance tested at 400 ms was no different than performance with no mask at 500 ms (also indicative of what it might have been at 400 ms). The immediate mask had no effect on performance in the randomized locations condition. Thus, it was concluded that iconic memory had a role to play in performance in the unchanged locations condition at 0 ms, but not at a delay of 300 ms or thereafter.

Since iconic memory played a role in performance only in the unchanged locations condition, but not in the randomized locations condition, it indicated that preserved configurational information in the icon aided performance in the unchanged condition. Experiments 11, 12, and 13 tested the importance of configural encoding in the performance of the participants by contrasting simultaneous and sequential presentation of stimuli in the study display. Experiment 11 used simultaneous presentation. Experiment 12 used sequential presentation such that stimuli were presented one by one to build up the study display, preserving configurational information to a large extent. Experiment 13 used sequential presentation, such that the previous stimulus vanished as the next was presented, and thus did not allow the participants to view the configuration of the display at all. In this case, any configural encoding would have been dependent on building a memory-based representation of the array as each item was presented. Results showed no difference between performance in Experiments 11 and 12, but a severe disruption of performance in the unchanged locations condition in Experiment 13, reiterating the role of configurational information in this condition, analogous to the experiments using masks.

Nevertheless, in the immediate mask experiment as well as in Experiment 13 which precluded configurational encoding, a small but significant difference remained between the unchanged and randomized locations conditions. This was evidence of items transferred to a more durable store than iconic memory and in which they were maintained till at least 2500 ms, the longest study-test interval in this research.

The representations in this more durable store would have to be spatiotopic, at least initially, for that would explain some of the difference between the unchanged and randomized locations condition. The items in this store match the test display in the unchanged locations condition, mismatch the test display in the randomized locations condition, and thus yield a difference between the two conditions. This store could be the large capacity, fragile VSTM postulated by Sligte et al. (2008) but for the finding that the difference remained significant till about 2500 ms, far outlasting the time period associated with the proposed large capacity fragile VSTM. Thus, it was concluded that performance after the mask manifested the items that were held as bound objects in a relatively robust and more permanent store, possibly similar to VSTM proposed by Phillips (1974).

This relatively permanent store was also explored with the help of subsequent Experiments 12, 13, and 14, which used sequential presentation of stimuli. The data from these experiments showed both primacy as well as recency effects. This finding is important because of three reasons. First, binding is usually considered to be the result of simultaneous processing. Adherents of synchrony would find it rather hard to explain how stimuli would be encoded according to their positions in a sequence. Indeed, studies of perceptual binding show that temporal synchrony, or simultaneous presentation, is crucial for feature binding (Fahle & Koch, 1995; Keele et al., 1988). Those who hold that binding occurs due to conjunctively coded neurons also assume that as one object is selected, the others are deselected or recede to the background and are perhaps eventually lost from the system (Duncan, 2006). From the experiments on sequential presentation, it is clear that the stimulus is also encoded according to the context in which it appears; a context that is provided by the position it occupies in a series. Thus, the process of binding utilizes the other representations in the field – whether presented at the same time or not.

A second reason why the serial position effects are important is that the participants were not explicitly asked to remember sequential order. Indeed the request was to remember selected features, colour and shape, and ignore locations. Such instructions would have increased the focus on the items to be remembered rather than the sequence in which they were presented. Obtaining serial position effects in spite of such instructions suggests that serial positions were automatically encoded along with the stimulus representations.

The task used in the present research is a third reason why the observation of both primacy and recency effects is interesting. The change detection task with whole displays is akin to a recognition task in that the representations held in memory need to be matched with each of the items in the study display one by one, and a decision is to be made whether or not each one is same or different in the binding of relevant features. Indeed, Allen et al. (2006) used a recognition score as the dependent measure in their experiments on bindings in VWM. As indicated by the review of research in the area of visuo-spatial WM, bow shaped serial position effects are found in tasks requiring serial reconstruction, but are rarely found with recognition tasks. In fact recognition tasks are often presumed to test item memory rather than memory for serial order. Avons (1998) contended that the serial position effect is task dependent. Ward, Avons and Melling (2005) provided subsequent confirmatory evidence with bow shaped curves obtained for serial reconstruction of order, but not when a two alternative forced choice test of recognition was used. Finding primacy and recency effects despite such contrary theorizing and research evidence, in a task similar to recognition, is therefore, exciting.

It appears that serial positions of the stimuli in the present experiments are a factor in encoding rather than an artefact of retrieval. The regularity in the pattern supports the idea the serial position effects simply manifest the activation of items according to the sequential position of their presentation. The interactions obtained in Experiment 14, also confirm this inference. In this experiment, the three-factor interaction between study-test intervals, study-display durations, and serial position effects was found to be significant. It was found that the pattern of serial position effects with the three study-display durations varied between 0 and 2000 ms. Especially with the study-display duration of 200 ms, i.e., 33.3 ms per item, it was found that the primacy effect shown at 0 ms decreased at 2000 ms, whereas a recency effect which was not apparent at 0 ms, was shown at 2000 ms. It was surmised that the primacy effect was shown at 0 ms, but was lost at 2000 ms as the level of activation gradually reduced. The primacy effect shown at 0 ms cannot be explained as rehearsal as the exposure of the stimulus is only 33.3 ms per item, and thus too short for any explicit strategy to become operational. In contrast, the recency effect does not appear at 0 ms. With regard to the recency effect, it is noteworthy that there was a trend towards negative recency at 0 ms, when the study-display duration was 200 ms. There was no such negative recency shown at study-test intervals of 900 and 1500 ms. This implies that the lack of recency with the study-display duration of 200 ms could not be due to interference from the test display, for there is no reason for interference to be any less with study-display durations of 900 or 1500 ms. Also, the lack of recency at 0 ms, but a significant recency effect shown at 2000 ms, with a study-display duration of 200 ms, could be due to inhibition of irrelevant features and selective consolidation of relevant features over a period of time, which was also evident in the randomized locations condition in the previous experiments in this research.

MORE YIN THAN YANG: THE PROCESS OF INHIBITION

The robust finding across experiments that performance improved over the study-test intervals studied in the randomized location condition was evidence that the process of inhibition was at work in these experiments. Nevertheless, this same finding can also be construed as a slow process of consolidation in the randomized locations condition. Indeed the two processes are complementary and probably difficult to disentangle.

Nevertheless, to a substantial extent this was achieved by the experiments using a mask. Immediate and delayed masks were used to dissociate the peripheral and central processes that follow the initial registration of stimuli. Turvey (1973) and Bongartz and Scheerer (1976) had also used masks at different delays to distinguish between early peripheral processes in the visual system and the later, central processes. Analogous to claims that information persisted beyond the retinotopic stage of iconic memory (Breitmeyer et al., 1982; Coltheart, 1980; Feldman, 1985, McRae et al., 1987; Smithson & Mollon, 2006), Potter (1976) had postulated two kinds of masking effects, perceptual and conceptual, affecting respectively, the perceptual processes which required presence of the stimulus or an icon, and the subsequent conceptual processes which built on the perceptual processes. This idea was used by Intraub (1984) as well as Loftus and Ginn (1984), and more recently by Sligte et al. (2008).

Masks have also been used to study the process of consolidation in VWM by many researchers (Vogel et al., 2006; Woodman and Vogel, 2005, 2008; Zhang and Luck, 2008). In contrast, there is little evidence of a mask being used to study inhibition. Nevertheless, using the preview search procedure, which is an experimental paradigm very close to the one used in the present research, Watson and Humphreys (2005) reported that when another set of related stimuli are introduced in the preview period, they diminish the advantage associated with the preview of the first set of distracters. However, flashing a set of distracters on and off, in the beginning of the preview period disrupted the preview benefit, whether or not the distracters were related to the original preview stimuli. Introducing another set of related stimuli during the preview period is similar to using a using a conceptual mask after a delay, while flashing a set of distracters at the beginning of the preview period is similar to an immediate perceptual mask or energy mask, and presumably affecting peripheral processing of the initial set of distracters, thus reducing the preview benefit.

Recognizing the confound between the kind of mask and the timing of mask in most earlier studies, and desirous of attributing any effects of the mask only to its timing, a single type of mask having both perceptual and conceptual properties was created and used in the present research. The mask was presented to the participants for 100 ms either immediately after the study display (Experiment 9) or after a delay of 300 ms (Experiment 10), and both were compared with baseline performance without a mask (Experiment 8). It is the randomized locations condition in these experiments, which is the focus of this discussion, for it is in this condition that inhibition was applicable and manifest in Experiment 8. The results showed that when tested immediately after a delayed mask, performance improved, not only in comparison to the no mask and immediate mask experiments, but also in comparison to the asymptotic performance observed later on. Indeed, this improvement removed the gap between unchanged and randomized conditions observed in all other experiments and made this performance statistically similar to the one in the unchanged locations condition.

It is inferred that this performance showed what was in VWM at that point of time. That it was more and not less than the asymptotic performance is explained by the fact that a factor of inhibition influences performance in all previous experiments in the randomized locations condition. This inhibitory factor, which is otherwise the dominant force in the randomized locations condition, is interrupted or interfered with by the mask. This experiment demonstrated that consolidation of bindings is a selective process, for the increased performance after the mask at 400 ms, represents the consolidation of relevant features into VWM which is statistically no different in the unchanged and randomized locations condition. What is deleted from among the factors affecting performance at the post-mask test at 400 ms is inhibition. The factor of inhibition is most prevalent in performance around 500 ms after stimulus onset as shown by studies of attentional blink (Chun & Potter, 1995), and preview search (Humphreys et al., 2004; Watson & Humphreys, 1997). In the present research, this process of inhibition presumably peaks around 500 ms after stimulus onset, was interrupted by the mask, and hence the post mask performance is dictated only by what was selectively consolidated into VWM before the mask.

Woodman and Vogel (2008) have also concluded that consolidation is selective from their study using masks at various delays after the sample array in a change detection task. Their conclusion is based, however, on the differential processing of colour, in that performance for colour was better than orientation, shape, and conjunction, conditions. This was also substantiated by studying the CDA component of ERPs. It is noteworthy that this distinction emerged gradually as the stimulus-mask SOA increased.

Thus the ongoing process that results in a coherent object is the process of selective consolidation and concomitant inhibition. The mask essentially interrupts this basic ongoing process. It is a source of interference in consolidation as well as inhibition. The target features as dictated by task instructions are selectively consolidated and the irrelevant feature is inhibited by the participants. The delayed mask interrupts both these central processes, and performance reflects only what has been selectively consolidated into VWM up until the mask appears.

Though the present studies are all behavioural and did not use any physiological measures, it is speculated that the delayed mask affected the reentrant processes that confirm the representation of the stimuli initially fed into the visual system by feed forward processes. This speculation is supported by two kinds of evidence available in current literature. First inhibition is postulated to be accompanied by the reentrant activity of long range excitatory neurons in the brain, yielding increased activation in brain regions that are associated with behavioural results of inhibition as assessed by distracter suppression (Serences et al., 2004), negative priming (Wright et al., 2006), and the preview search procedure (Allen et al., 2008). The second line of evidence comes from studies showing that a mask affects reentrant processes (Di Lollo et al., 2000; Enns & Oriet, 2007; Fahrenfort et al., 2007). Indeed, Fahrenfort et al. (2007) established that a delayed mask interrupts reentrant but not feed forward processing. There is also converging evidence that TMS affects reentrant processes and disrupts binding (Braet & Humphreys, 2009). It is well known that the TMS pulse is similar to a mask in its effects (Amassian et al., 1989; Kammer, 2007). Nevertheless, the contention that the delayed mask affected reentrant processes is a speculation, not a conclusion from the present data, and a hypothesis to be explored in future by combining this paradigm with physiological measures.

The different result of the delayed mask experiment as compared to the experiment with no mask also belies the suggestion that in all the other experiments in the present research, the test display acts like a mask, overwriting the memory of the study display. Such a suggestion is inherent in the analysis of the switch detection task by Alvarez and Thompson (2009). They allege that the poor performance on the switch detection task is due to problems in maintaining bound objects in VWM because new perceptual input from the test display presumably overrides the previous one and forces rebinding of information. But this argument for similarity between the test display and a mask is true only to the extent that the test display as well as a mask might act to interfere with the processing of the study display. Empirically, they are associated with different cognitive demands. The mask is to be ignored, whereas the test display cannot be ignored. Indeed, it has to be compared with the representations from the study display, and hence both the study and the test display must be available for comparison. The test display is like a conjunction search task (if compared with visual search tasks), and like a test of recognition (if compared to a test of memory), in that the stimuli held in the target template, or memory, need to be matched with each of the items in the study display one by one, and a decision is to be made whether or not each one is same or different in the binding of relevant features.

To return to the nature of the process interrupted by the mask, Experiment 11 confirmed that the kind of inhibition seen in these experiments is a post perceptual VWM process. In this experiment the display duration was increased from 200 to 900 and 1500 ms. This improved performance overall, but had no differential effect at the two study-test intervals of 0 and 2000 ms. This indicated that the inhibition of irrelevant features did not happen during the presentation of the study display, and is not a factor operational during encoding, but that it is a post-perceptual process within WM. Analogously a number of studies with the preview search procedure have suggested that ‘active inhibition’ is a higher order process that follows the initial registration of the stimuli (reviewed by Soto et al., 2008).

It is proposed that the emergence of the bound object in VWM is a result of the inhibitory process. It is recognized that the concept of inhibition has many different connotations. It may also be used in the present experimental paradigm in different ways. The task being above capacity, focusing is required to select a region, objects, or features, to manage the task even before the trial begins. This uses the prioritization function of attention. This selection process necessitates that the rest of the locations, objects, and features are deselected. These would not influence or reappear in performance at 2000 ms. Thereafter, from the selected representations, of features, objects, or locations, there is a process of removal of the irrelevant, unwanted feature. This process begins only when capacity is full and as much as possible of the study display has been encoded. This crucial process is presumably a part of the central executive component of WM, and comes into play to extract meaning from an otherwise confusing array of stimulus dimensions. Gradually, this inhibitory process is complete, and the object comprising relevant features emerges to be maintained in WM, ready for further processing. Supportive evidence comes from fMRI studies by Sala and Courtney (2007) who found reduced activity over time in reaction to ‘conjunction’ stimuli in cortical regions dedicated to ‘what’ and ‘where’ stimuli. Interestingly, this reduction does not happen for only ‘what’ or only ‘where’ stimuli. It happens only following bound stimuli which use both these streams of processing.

This inhibitory process is rather different from the orientation function of attention that allows selection of locations and/or objects from the stimulus display that is presented. Indeed it is possible to focus and use this latter type of attention even before the stimuli are displayed or in the complete absence of distracters (Henderson, 1996). In contrast, the inhibitory process occurs after stimulus presentation and seems to be directed at everything that is irrelevant in the stimulus display – be it features or objects. In this sense, it is similar to distracter suppression, which appears only after the distracters are identified (Luck, 1998; Luck et al., 1997; Luck & Hillyard, 1994a, 1994b).

In the area of WM, an inhibitory process was first proposed by Hasher and Zacks (1988) to account for differences among older and younger adults in WM. They proposed that successful processing implied allowing relevant information in and keeping irrelevant information out. However, they did not apply this idea to features within bindings, and restricted their view to objects in WM. Subsequent studies have shown that the memory problems of older adults are not so much regarding individual features but about bindings of those features (Chalfonte & Johnson, 1996; but see Brockmole, Parra, Della Sala, & Logie, 2008). The gradual process of deleting or inhibiting a feature that is task-irrelevant and possibly disruptive has been identified as an important aspect of WM executive functions (Friedman & Miyake, 2004; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000).

Presumably all features and objects, indeed the whole display, enter the sensory register of the participants, and gradually, from this representation, the relevant features and objects are selected and retained, and the irrelevant ones are discarded. Whether the features participate in a preliminarily integrated percept to be refined thereafter or whether the features are held in separate features maps is a moot point. The vast literature on information processing theory has shown that parallel representation of stimulation followed by serial decision making is a much more efficient procedure, than selecting each object one by one and making decisions about it (e.g., Sternberg, 1966, 1967). It being easier to encode all stimuli and then make the decisions, participants might loosely represent the irrelevant as well as relevant features initially, deleting the irrelevant ones only after the display is gone, and no more relevant features can be committed to memory. Certainly, however, there is no clear, coherent, strong object right from the outset. The deletion of features from within a representation, such that it becomes a coherent strong object capable of further manipulation, takes time and resources, and is a preliminary phase in the online processing of objects in WM.

It is debatable whether this process happens in the episodic buffer, for the concept of the episodic buffer itself is yet to be fully explored and delineated. It is accepted that Baddeley and associates no longer think of feature binding as taking place within the buffer (Allen et al., 2006; Baddeley et al., 2009; but see Allen et al., 2009). It is contended that this is essentially because they view feature binding as an automatic, instantaneous integration of features. They do allow the notion that further processing of bindings (as per their definition) can and probably does occur in the buffer. As conceptualized in this thesis however, the process of binding is the preliminary phase of object processing in VWM.

THE PROCESS OF BINDING

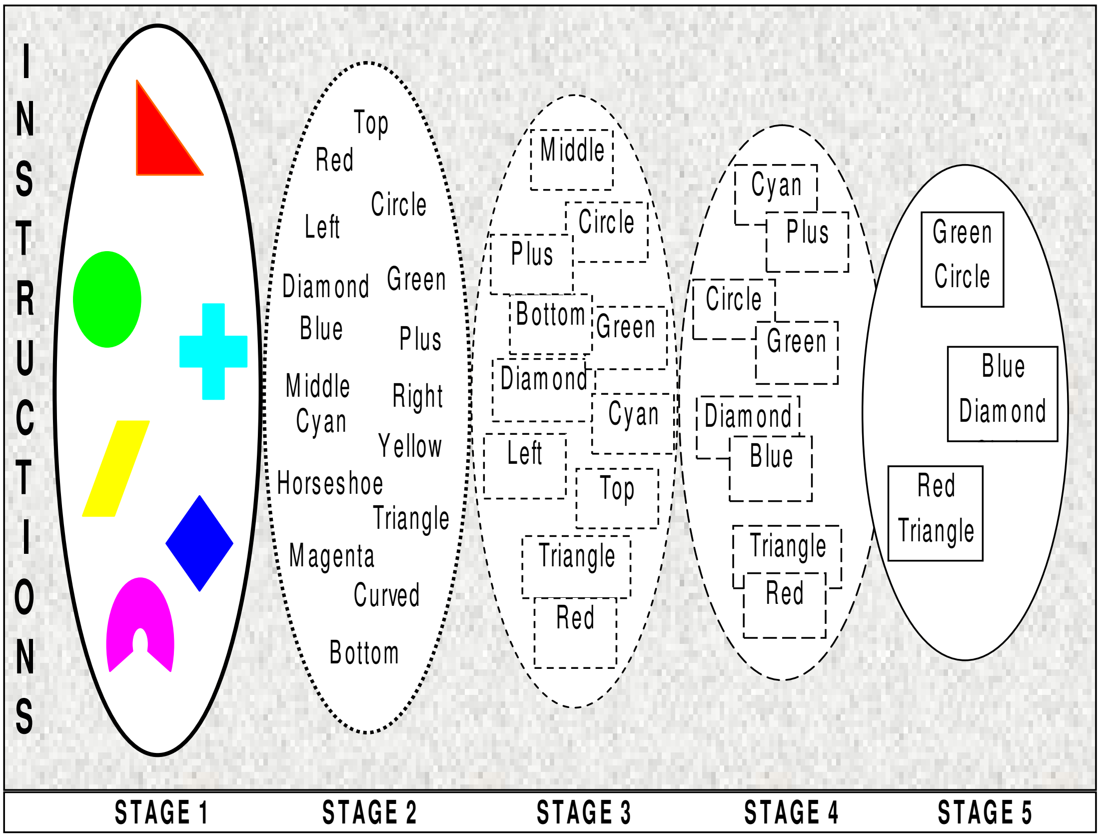
The process of binding as understood on the basis of the experiments reported in this thesis is illustrated in Figure 9.1 with some of the stimuli used in this research taken as exemplars.

The five stages represent cross-sections of the process to aid understanding, otherwise the process is assumed to be continuous. The area covered by the ovals gradually reduces to depict the decrease in the amount of information available to the participant, and also increasingly focused attention. It is, nevertheless, accepted that attention plays different kinds of roles in this process. The gradual completion of the boundaries is used to show the increasing clarity of the representations.

The whole process is dictated and delimited by instructions from WM which define the goal for the participant. Even before the trials begin, the participant is set to ignore the irrelevant feature. Stage 1 represents stimuli in the real world. Stage 2 is the initial representation of the stimulus dimensions, which includes almost all the various features defining the stimuli. However, there is some loss of information even at this early stage, as a proportion of the stimuli impinging on the sense organs are selected to be processed further. This stage contributes to the binding process by holding information as an almost veridical representation of reality which can be organized and further consolidated. It corresponds to the retinotopic iconic memory, and is vulnerable to an immediate mask. It is also difficult to build up this representation with sequential presentation such that one item vanishes as the subsequent one is presented, as shown by Experiment 13.

Figure 9.1

The process of binding



Stage 3 is a spatiotopic representation with a greater loss of information than Stage 2, but which has much more information available than the later stages. Presumably it corresponds to the fragile VSTM proposed by Sligte et al. (2008). The process of active inhibition is dominant between the Stages 3 and 4, and removes the irrelevant feature, in this case locations. The inhibitory process is otherwise a necessary component of top-down processes which select relevant information and inhibit irrelevant information and operates throughout the binding process. This top-down processing is achieved by reentrant processes. Notice how reentrant processes recover the relevant feature 'blue' to be amalgamated with 'diamond' as represented in the next stage. The delayed mask probably disrupts these reentrant processes. Stage 4 represents only the relevant features, with increasing overlap between them to show the strength of binding at this stage. Stage 5 shows features bound as objects in VWM ready for further processing. Though the illustration uses location as the feature to be ignored, it is assumed that analogous processes operate if colour or shapes (or other stimulus dimensions) are to be ignored. The total duration of this process will vary with the stimulus dimensions involved. As per the evidence from Experiments 2, 3, and 4, replicated by Experiments 5, 6, and 7, the duration of the process is shorter when shapes or colours are to be ignored.

Can any information be directly transferred to WM at all? Is it possible for some information to bypass these stages and appear in VWM? One may speculate that the stage sequence is invariant, though the time scale can be considerably shortened if the broad attentional window includes a narrowly focussed mechanism that achieves this. This narrow focus may be due to top-down factors, say, an ‘intention’ to remember all red items, or all curved items, or the first item presented, or a red plus because it evokes associations with the Red Cross. Such an intentional focus would necessarily involve activated representations in LTM. Alternatively, it may at times, result from the higher activation level of a particular item due to bottom-up stimulus factors such as salience, first or last serial position, etc. It is the transactions between top-down and bottom-up processes which determine the course of the binding process, though the final outcome is contingent on the dictates of the task goals held in WM.

RECAPITULATION

To summarize, the *leit motif* of this thesis is that binding is a process, not a static entity. This process involves bottom-up information by features but is directed by top-down factors. Among the top-down processes, inhibitory control, achieved though attention, is of major importance, considering that the external world comprises a plethora of physical dimensions as stimuli that may be relevant or irrelevant to the task. As James affirmed over a century ago in the conclusion of his chapter on Will, "*Inhibition is therefore not an occasional accident; it is an essential and unremitting element of our cerebral life*" (James, 1890, Vol. II, Chapter 26, p.583, his italics).

CHAPTER 10

THE STORY SO FAR… …AND NEW BEGINNINGS

The present work explored the role of top-down and bottom-up factors in the process of binding of visual features. Researchers have often assumed binding to be an instantaneous integration of all diverse features into a coherent object. In a large measure this might have been dictated by the precision of the measurement tools and techniques available to cognitive science. The empirical results here show that binding is a process that takes time to finally result in a coherent object, and during this time it is affected by many different variables. The process is not immune to perceptual differences among features. Hence it is neither instantaneous nor automatic. Attention plays myriad roles in this process. Further, post-perceptual, active inhibition of irrelevant elements is the top-down WM process that plays a dominant role in the process of binding. This thesis indicates that a revision of the assumption that instantaneous binding results in strong objects, is requisite.

Nevertheless, this research is not a demolition exercise. It took extant theories and literature as the basic groundwork to explore the process of binding. Being exploratory, it necessarily has a broad focus and could consider only some of the major issues and debates in this area, such as the role of different features, attention, consolidation, and inhibition. Moreover, it was decided to study this process at equal time intervals varying by 500 ms, rather than time-intervals indicated by literature (and subsequently confirmed), to be more important in this process. Since it was important to explore the trends in the process, this was a necessary choice, but it is nevertheless an important limitation of this work.

But future studies can ameliorate the limitations of the present ones, add new knowledge, and will possibly throw up new questions! The experiments fall in rather distinct groups, and indeed, each set of experiments provide a foundation for the visualization of further studies. To aid the latter process, an exploration of the possible avenues of future research and experiments is in order.

Experiments 1-7 which compared the differential role of location, shape, and colour in the binding process until 2500 ms can be extended beyond that study-test interval to assess how far features are maintained as bindings, and when, and why, a bound object disintegrates. It would also be interesting to explore what happens to features once they are bound. Do they interact such that they inherit the costs and benefits associated with other features? A recent study by Guerard et al. (2009) suggests that this might be so. They found that phonological similarity was detrimental to the recall of letters as well as locations when they are bound together. The same, however, may or may not apply in the visuospatial domain of WM.

On the other hand, there can also be a downward extension of the project, keeping in mind the limitation that after 0 ms, the lowest study-test interval used here was 500 ms (except in Experiment 1, which used 200 ms as well). The experiments with masking show that what happens during the first 500 ms or so is crucial in this process which otherwise lasts till about 1500 ms. Thus studies with finer gradations of study-test intervals are necessary. Since behavioural measures are rather coarse, it would be judicious to use temporally precise physiological measures such as the ERPs in conjunction with the experimental paradigm used here to fully explore the variables affecting binding from 0-1500 ms. ERPs have been combined with change detection tasks (e.g., Luria, Sessa, Gotler, Jolicoeur, & Dell Acqua, 2009). Using N2pc, the role of spatial attention in the binding process has been shown (Hyun et al. (2009). It is quite well established that N2pc is an early measure of distracter suppression (Luck, 1998; Luck et al., 1997; Luck & Hillyard, 1994a, 1994b; Robitaille & Jolicoeur, 2006), whereas CDA or SPCN is associated with VWM (Jolicoeur et al., 2008; Robitaille & Jolicoeur, 2006; Vogel & Machizawa, 2004). It would be interesting to study whether these two ERP components are differentially affected by the immediate and delayed masks.

An entirely new area of exploration has been opened up with the observation of serial position effects in binding with sequentially presented stimuli. Bow shaped curves suggest that stimuli are activated according to their serial positions and this differential encoding affects the detection performance of the participants. It is debatable how far these activations involve LTM. There are many views which postulate that activation at the time of encoding involves associations with LTM (Burgess & Hitch, 2005, 2006; Davelaar, Goshen-Gottstein et al., 2005; Davelaar, Usher et al., 2008; Logie, 1995, 2003). Thus the role of LTM in the binding process is also an interesting avenue to explore. One way to tease out if the stimuli are evoking LTM representations would be to combine a priming paradigm with the present one. Priming operates due to activation of LTM representations (e.g., Kristjansson, 2008). There is evidence that visual search for features or objects can be primed (Kristjansson, 2006; Kristjansson et al., 2008). If swap detection performance can be primed, it would be one way of demonstrating that LTM representations are being evoked even at the early stage of binding. If the sequential presentation paradigm is used, and priming modulates the serial position effects observed in the present research, it would shed light on the debate regarding whether activation is limited to STM, or if LTM representations are concomitantly evoked in the process of binding.

These offshoots are but some examples of the potential inherent in the paradigm used in the present research. They are also testimony to the worth of knowledge that it has already generated about the process of binding.

To conclude, the main findings presented in this thesis are:

1. Binding of task-relevant visual features coupled with removal of the influence of task-irrelevant features, such that a coherent object capable of further manipulation emerges, is a process that takes time.

2. This process is influenced by bottom up factors as manifested by differential processing of features (Comparisons of Experiments 2, 3, and 4; and 5, 6, and 7).
3. Nevertheless, the task relevance of features is the overriding factor of importance in the binding process. Relevant features are selectively consolidated and irrelevant features are inhibited (Experiments 1-8).
4. Iconic memory has a role to play in the process of binding of relevant visual features (Experiment 9).
5. The inhibition of irrelevant features is post-perceptual active inhibition (Experiments 10 and 11).

There were, at least, two other interesting findings, which require further thorough investigation. First, different kinds of attention – object based, feature based and spatial attention – seemingly affect binding in a different manner, dependent on which features are involved in binding (Comparisons involving Experiments 2, 3, 4, 5, 6, 7 and 8). Second, if stimuli are presented in a sequence, serial position seems to be inevitably encoded (Experiments 12, 13, and 14).

Based on these empirical contributions with the relatively novel experimental paradigm, the thesis ends with proposing a model of the binding process (Chapter 9) that summarizes the findings so far, and may be used as a rudimentary framework for future research.

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APPENDICES

APPENDIX A

TABLES FOR CHAPTER 4

Table 4.1
d primes and beta for each study-test interval for unchanged and randomized locations in Experiment 1 (N=10)

Experiment 1	d'				beta			
Study-test interval	Unchanged locations		Randomized locations		Unchanged locations		Randomized locations	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.049	0.708	0.501	0.518	5.133	3.361	2.073	2.665
200 ms	1.986	0.505	0.636	0.677	4.913	2.799	2.140	1.744
1500 ms	1.122	0.562	0.815	0.406	1.873	1.286	1.673	0.784
2800 ms	0.893	0.412	0.964	0.595	1.727	1.346	1.757	0.671
4100 ms	0.680	0.323	0.728	0.458	1.284	0.398	1.452	0.501
Average	1.546	0.502	2.986	1.838	0.729	0.531	1.819	1.273

Table 4.2
ANOVA for each study-test interval for unchanged and randomized locations in Experiment 1 (N=10)

Source	df	MS	F	p	partial η²
Unchanged/Randomized (A)	1	16.705	86.481	0.000	0.906
Error(Unchanged/Randomized)	9	0.193			
Study-test intervals (B)	4	3.481	19.922	0.000	0.689
Error(Study-test intervals)	36	0.175			
A × B	4	6.347	34.466	0.000	0.793
Error(A × B)	36	0.184			

Table 4.3
d primes for colour swaps and shape swaps for each study-test interval for unchanged and randomized locations in Experiment 1 (N=10)

Experiment 1	Unchanged locations				Randomized locations			
Study-test interval	Colour swap		Shape swap		Colour swap		Shape swap	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	2.759	0.743	3.212	0.646	0.589	0.649	0.411	0.530
200 ms	1.477	0.542	2.623	0.702	0.685	0.782	0.580	0.654
1500 ms	1.020	0.571	1.231	0.599	0.723	0.408	0.907	0.481
2800 ms	1.109	0.413	0.693	0.473	0.912	0.514	1.049	0.845
4100 ms	0.877	0.538	0.537	0.376	0.727	0.479	0.731	0.494
Average	1.449	0.561	1.659	0.559	0.727	0.566	0.735	0.601

Table 4.4
ANOVA for colour swaps and shape swaps for each study-test interval in the unchanged locations condition in Experiment 1 (N=10)

Source	df	MS	F	p	partial η^2
Swaps (A)	1	1.108	4.947	0.053	0.355
Error(Swaps)	9	0.224			
Study-test intervals (B)	4	18.117	44.725	0.000	0.832
Error(Study-test intervals)	36	0.405			
A × B	4	2.037	16.552	0.000	0.648
Error(A × B)	36	0.123			

Table 4.5
ANOVA for colour swaps and shape swaps for each study-test interval in the randomized locations condition in Experiment 1 (N=10)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.002	0.010	0.923	0.001
Error(Swaps)	9	0.169			
Study-test intervals (B)	4	0.661	2.291	0.078	0.203
Error(Study-test intervals)	36	0.288			
A × B	4	0.118	0.970	0.436	0.097
Error(A × B)	36	0.122			

APPENDIX B

TABLES FOR CHAPTER 5

Table 5.1
d primes and beta for each study-test interval for unchanged and randomized locations in Experiment 2 (N=12)

Experiment 2	d'				beta			
Study-test interval	Unchanged locations		Randomized locations		Unchanged locations		Randomized locations	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.600	0.648	0.510	0.587	7.661	2.501	1.496	0.636
500 ms	1.764	0.919	0.806	0.487	4.657	3.367	2.011	1.284
1000 ms	1.364	0.501	0.809	0.495	2.417	2.374	1.762	1.268
1500 ms	1.212	0.560	0.977	0.416	2.390	2.565	1.689	0.703
2000 ms	1.363	0.550	1.138	0.457	2.214	1.589	2.545	2.520
2500 ms	0.905	0.524	0.750	0.440	1.521	0.589	1.461	0.471
Average	1.701	0.617	3.477	2.164	0.832	0.480	1.827	1.147

Table 5.2
ANOVA for each study-test interval for unchanged and randomized locations in Experiment 2 (N=12)

Source	df	MS	F	p	partial η^2
Unchanged/Randomized (A)	1	27.233	44.958	0.000	0.803
Error(Unchanged/Randomized)	11	0.606			
Study-test intervals (B)	5	4.210	27.903	0.000	0.717
Error(Study-test intervals)	55	0.151			
A × B	5	7.640	33.517	0.000	0.753
Error(A × B)	55	0.228			

Table 5.3
d primes for colour swaps and shape swaps for each study-test interval for unchanged and randomized locations in Experiment 2 (N=12)

Experiment 2	Unchanged locations				Randomized locations			
Study-test interval	Colour swap		Shape swap		Colour swap		Shape swap	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.434	0.652	3.525	0.432	0.489	0.648	0.528	0.632
500 ms	1.670	0.946	1.895	0.951	0.861	0.610	0.752	0.494
1000 ms	1.342	0.401	1.406	0.666	0.803	0.532	0.809	0.518
1500 ms	1.211	0.659	1.220	0.521	0.983	0.499	0.978	0.450
2000 ms	1.334	0.617	1.424	0.619	1.103	0.589	1.177	0.376
2500 ms	0.907	0.634	0.928	0.509	0.672	0.393	0.834	0.576
Average	1.650	0.651	1.733	0.616	0.819	0.545	0.846	0.508

Table 5.4
ANOVA for colour swaps and shape swaps for each study-test interval in the unchanged locations condition in Experiment 2 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.251	1.099	0.317	0.091
Error(Swaps)	11	0.229			
Study-test intervals (B)	5	20.302	47.649	0.000	0.812
Error(Study-test intervals)	55	0.426			
A × B	5	0.036	0.410	0.840	0.036
Error(A × B)	55	0.087			

Table 5.5
ANOVA for colour swaps and shape swaps for each study-test interval in the randomized locations condition in Experiment 2 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.027	0.191	0.671	0.017
Error(Swaps)	11	0.143			
Study-test intervals (B)	5	1.099	3.415	0.009	0.237
Error(Study-test intervals)	55	0.322			
A × B	5	0.049	0.566	0.726	0.049
Error(A × B)	55	0.086			

Table 5.6
d primes and beta for each study-test interval for unchanged and randomized shapes in Experiment 3 (N=12)

Experiment 3	d'				beta			
Study-test interval	Unchanged shapes		Randomized shapes		Unchanged shapes		Randomized shapes	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.440	0.703	1.171	0.547	6.720	3.261	1.386	0.406
500 ms	1.875	0.402	1.482	0.551	3.416	2.389	2.145	1.161
1000 ms	1.809	0.474	1.510	0.517	2.428	1.220	2.181	1.211
1500 ms	1.436	0.804	1.465	0.682	2.404	2.390	2.434	2.342
2000 ms	1.618	0.792	1.386	0.538	2.685	2.505	1.891	1.195
2500 ms	1.254	0.757	1.146	0.487	1.728	0.595	1.491	0.561
Average	1.905	0.655	1.360	0.554	3.230	2.060	1.921	1.146

Table 5.7
ANOVA for each study-test interval for unchanged and randomized shapes in Experiment 3 (N=12)

Source	df	MS	F	p	partial η^2
Unchanged/Randomized (A)	1	10.706	24.096	0.000	0.687
Error(Unchanged/Randomized)	11	0.444			
Study-test intervals (B)	3	6.059	13.594	0.000	0.553
Error(Study-test intervals)	30	0.446			
A × B	5	4.409	24.105	0.000	0.687
Error(A × B)	55	0.183			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 5.8
d primes for colour swaps and shape swaps for each study-test interval for unchanged and randomized shapes in Experiment 3 (N=12)

Experiment 3	Unchanged shapes				Randomized shapes			
Study-test interval	Colour swap		Location swap		Colour swap		Location swap	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.122	0.725	3.543	0.495	1.210	0.890	1.199	0.442
500 ms	1.648	0.496	2.175	0.474	1.522	0.720	1.472	0.500
1000 ms	1.653	0.645	2.033	0.499	1.589	0.578	1.456	0.592
1500 ms	1.375	0.764	1.529	0.912	1.541	0.846	1.420	0.645
2000 ms	1.676	0.81	1.582	0.825	1.497	0.550	1.307	0.645
2500 ms	1.349	0.946	1.202	0.65	1.188	0.469	1.133	0.625
Average	1.804	0.731	2.011	0.642	1.425	0.676	1.331	0.575

Table 5.9
ANOVA for colour swaps and shape swaps for each study-test interval in the unchanged shapes condition in Experiment 3 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	1.545	6.754	0.025	0.380
Error(Swaps)	11	0.229			
Study-test intervals (B)	5	13.050	25.660	0.000	0.700
Error(Study-test intervals)	55	0.509			
A × B	5	0.477	4.460	0.002	0.288
Error(A × B)	55	0.107			

Table 5.10
ANOVA for colour swaps and shape swaps for each study-test interval in the randomized shapes condition in Experiment 3 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.313	1.031	0.332	0.086
Error(Swaps)	11	0.304			
Study-test intervals (B)	5	0.593	1.737	0.141	0.136
Error(Study-test intervals)	55	0.341			
A × B	5	0.026	0.175	0.971	0.016
Error(A × B)	55	0.148			

Table 5.11
d primes and beta for each study-test interval for unchanged and randomized colours in Experiment 4 (N=12)

Experiment 4	d'				beta			
Study-test interval	Unchanged colours		Randomized colours		Unchanged colours		Randomized colours	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.807	0.733	1.827	0.810	8.430	2.797	2.974	2.595
500 ms	2.205	0.891	1.607	0.581	4.048	2.915	2.776	2.443
1000 ms	1.864	0.597	1.395	0.632	3.112	2.503	2.225	2.386
1500 ms	1.444	0.662	1.289	0.461	2.133	1.253	1.805	1.177
2000 ms	1.352	0.621	1.084	0.880	1.853	1.238	2.031	1.623
2500 ms	1.386	0.562	1.013	0.702	1.950	1.225	1.671	1.226
Average	2.010	0.678	1.369	0.678	3.588	1.988	2.247	1.908

Table 5.12
ANOVA for each study-test interval for unchanged and randomized colours in Experiment 4 (N=12)

Source	df	MS	F	p	partial η²
Unchanged/Randomized (A)	1	14.774	23.573	0.001	0.682
Error(Unchanged/Randomized)	11	0.627			
Study-test intervals (B)	2	19.863	35.548	0.000	0.764
Error(Study-test intervals)	25	0.559			
A × B	5	2.727	11.493	0.000	0.511
Error(A × B)	55	0.237			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 5.13

d primes for colour swaps and shape swaps for each study-test interval for unchanged and randomized colours in Experiment 4 (N=12)

Experiment 4	Unchanged colours				Randomized colours			
Study-test interval	Location swap		Shape swap		Location swap		Shape swap	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.582	0.694	3.654	0.59	1.706	0.983	2.045	0.794
500 ms	2.306	0.941	2.132	0.888	1.726	0.696	1.537	0.677
1000 ms	2.047	0.591	1.674	0.61	1.459	0.648	1.348	0.671
1500 ms	1.553	0.802	1.367	0.805	1.215	0.434	1.393	0.591
2000 ms	1.529	0.682	1.21	0.678	1.181	0.852	0.993	0.978
2500 ms	1.488	0.617	1.339	0.661	1.016	0.722	1.026	0.747
Average	2.084	0.721	1.896	0.705	1.384	0.723	1.390	0.743

Table 5.14

ANOVA for colour swaps and shape swaps for each study-test interval in the unchanged colours condition in Experiment 4 (N=12)

Source	df	MS	F	p	partial η^2
Swaps (A)	1	1.269	6.569	0.026	0.374
Error(Swaps)	11	0.193			
Study-test intervals (B)	5	17.852	38.300	0.000	0.777
Error(Study-test intervals)	55	0.466			
A × B	2.361	0.306	0.941	0.417	0.079
Error(A × B)	25.968	0.325			
Underlined df indicates Greenhouse Geisser correction was applied					

Table 5.15
ANOVA for colour swaps and shape swaps for each study-test interval in the randomized colours condition in Experiment 4 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.002	0.011	0.918	0.001
Error(Swaps)	11	0.146			
Study-test intervals (B)	2.725	4.661	5.295	0.006	0.325
Error(Study-test intervals)	29.984	0.880			
A × B	5	0.276	1.900	0.109	0.147
Error(A × B)	55	0.145			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 5.16
ANOVA comparing Experiments 2, 3, and 4

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	7.586	3.841	0.032	0.189
Error	33	1.975			
Within-Subjects					
Unchanged/Randomized (B)	1	50.712	90.728	0.000	0.733
A × B	2	1.001	1.791	0.183	0.098
Error(Unchanged/Randomized)	33	0.559			
Study-test interval (C)	3	23.963	70.253	0.000	0.680
Error(Study-test interval)	105	0.341			
A × C	10	0.684	3.152	0.001	0.160
Error(Study-test interval)	165	0.217			
B × C	5	14.051	65.033	0.000	0.663
A × B × C	10	0.363	1.680	0.089	0.092
Error(B × C)	165	0.216			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 5.17
ANOVA comparing Experiments 2, 3, and 4 (Unchanged condition)

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	1.771	1.258	0.297	0.071
Error	33	1.407			
Within-Subjects					
Study-test intervals (B)	5	28.810	115.667	0.000	0.778
A × B	10	0.278	1.118	0.352	0.063
Error(Study-test intervals)	165	0.249			

Table 5.18
ANOVA comparing Experiments 2, 3, and 4 (Randomized condition)

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	6.816	6.051	0.006	0.268
Error	33	1.127			
Within-Subjects					
Study-test intervals (B)	4	0.629	2.586	0.043	0.073
Error(Study-test intervals)	125	0.243			
A × B	10	0.768	4.179	0.000	0.202
Error(Study-test intervals)	165	0.184			
Underlined df indicates value after applying Greenhouse Geisser correction					

APPENDIX C

TABLES FOR CHAPTER 6

Table 6.1
d primes and beta for each study-test interval for unchanged and randomized locations in Experiment 5 (N=12)

Experiment 5	d'				beta			
Study-test interval	Unchanged locations		Randomized locations		Unchanged locations		Randomized locations	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.513	0.493	0.431	0.461	8.914	1.654	1.504	1.240
500 ms	1.939	0.572	0.741	0.660	5.396	3.436	1.639	1.230
1000 ms	1.664	0.423	0.951	0.348	2.906	1.590	1.790	1.153
1500 ms	1.136	0.234	0.823	0.405	1.511	0.363	1.465	0.585
2000 ms	0.982	0.309	0.789	0.551	1.363	0.396	2.413	2.604
2500 ms	0.889	0.325	1.080	0.502	1.323	0.318	2.330	2.416
Average	1.687	0.393	0.802	0.488	3.569	1.293	1.857	1.538

Table 6.2
ANOVA for each study-test interval for unchanged and randomized locations in Experiment 5 (N=12)

Source	df	MS	F	p	partial η^2
Unchanged/Randomized (A)	1	28.173	46.974	0.000	0.810
Error(Unchanged/Randomized)	11	0.600			
Study-test intervals (B)	5	3.885	30.557	0.000	0.735
Error(Study-test intervals)	55	0.127			
A × B	5	8.305	62.222	0.000	0.850
Error(A × B)	55	0.133			

Table 6.3
d primes for colour swaps and shape swaps for each study-test interval for unchanged and randomized locations in Experiment 5 (N=12)

Experiment 5	Unchanged locations				Randomized locations			
Study-test interval	Colour swap		Shape swap		Colour swap		Shape swap	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.325	0.583	3.599	0.338	0.532	0.494	0.336	0.537
500 ms	1.806	0.543	2.094	0.697	0.774	0.680	0.715	0.716
1000 ms	1.772	0.652	1.61	0.449	1.044	0.525	0.834	0.431
1500 ms	1.06	0.324	1.213	0.364	0.721	0.461	0.930	0.529
2000 ms	1.029	0.357	0.951	0.36	0.680	0.568	0.902	0.613
2500 ms	0.734	0.368	1.067	0.391	1.066	0.399	1.096	0.729
Average	1.621	0.471	1.756	0.433	0.803	0.521	0.802	0.593

Table 6.4
ANOVA for colour swaps and shape swaps for each study-test interval in the unchanged locations condition in Experiment 5 (N=12)

Source	df	MS	F	p	partial η^2
Swaps (A)	1	0.651	2.502	0.142	0.185
Error(Swaps)	11	0.260			
Study-test intervals (B)	5	22.207	83.309	0.000	0.883
Error(Study-test intervals)	55	0.267			
A × B	5	0.258	2.434	0.046	0.181
Error(A × B)	55	0.106			

Table 6.5
ANOVA for colour swaps and shape swaps for each study-test interval in the randomized locations condition in Experiment 5 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.000	0.000	0.993	0.000
Error(Swaps)	11	0.082			
Study-test intervals (B)	5	1.131	4.742	0.001	0.301
Error(Study-test intervals)	55	0.239			
A × B	5	0.216	1.385	0.244	0.112
Error(A × B)	55	0.156			

Table 6.6
ANOVA comparing Experiments 2 and 5

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	1	0.034	0.036	0.852	0.002
Error	22	0.949			
Within-Subjects					
Unchanged/Randomized (B)	1	55.403	91.916	0.000	0.807
A × B	1	0.004	0.007	0.936	0.000
Error(Unchanged/Randomized)	22	0.603			
Study-test interval (C)	5	7.551	54.320	0.000	0.712
A × C	5	0.544	3.913	0.003	0.151
Error(Study-test interval)	110	0.139			
B × C	5	15.820	87.543	0.000	0.799
A × B × C	5	0.125	0.692	0.630	0.031
Error(B × C)	110	0.181			

Table 6.7
d primes and beta for each study-test interval
for unchanged and randomized shapes in Experiment 6 (N=12)

Experiment 6	d'				beta			
Study-test interval	Unchanged shapes		Randomized shapes		Unchanged shapes		Randomized shapes	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.258	0.718	1.096	0.454	7.891	2.740	1.306	0.301
500 ms	2.273	0.623	1.544	0.722	6.100	3.799	2.473	2.352
1000 ms	2.076	0.812	1.768	0.652	2.864	2.435	2.717	1.725
1500 ms	1.789	0.619	1.614	0.891	2.644	2.520	2.618	2.546
2000 ms	1.804	0.833	2.025	0.800	1.821	0.846	3.163	2.520
2500 ms	1.553	0.956	1.953	0.889	2.610	2.741	3.463	2.746
Average	2.125	0.760	1.667	0.735	3.989	2.514	2.623	2.032

Table 6.8
ANOVA for each study-test interval
for unchanged and randomized shapes in Experiment 6 (N=12)

Source	df	MS	F	p	partial η^2
Unchanged/Randomized (A)	1	7.578	9.681	0.010	0.468
Error(Unchanged/Randomized)	11	0.783			
Study-test intervals (B)	5	0.666	2.853	0.023	0.206
Error(Study-test intervals)	55	0.233			
A × B	5	5.131	23.820	0.000	0.684
Error(A × B)	55	0.215			

Table 6.9
d primes for colour swaps and shape swaps for each study-test interval for unchanged and randomized shapes in Experiment 6 (N=12)

Experiment 6	Unchanged shapes				Randomized shapes			
Study-test interval	Colour swap		Location swap		Colour swap		Location swap	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.099	0.688	3.375	0.744	1.234	0.648	0.993	0.435
500 ms	2.152	0.794	2.429	0.566	1.602	0.808	1.493	0.662
1000 ms	1.861	0.795	2.259	0.745	1.935	0.768	1.654	0.658
1500 ms	1.577	0.688	2.061	0.616	1.679	1.014	1.609	0.888
2000 ms	1.603	0.816	1.945	0.700	1.991	0.799	2.076	0.834
2500 ms	1.319	0.943	1.766	0.895	1.971	0.826	1.954	0.975
Average	1.935	0.787	2.306	0.711	1.735	0.811	1.630	0.742

Table 6.10
ANOVA for colour swaps and shape swaps for each study-test interval in the unchanged shapes condition in Experiment 6 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	4.955	48.871	0.000	0.816
Error(Swaps)	11	0.101			
Study-test intervals (B)	5	8.759	21.770	0.000	0.664
Error(Study-test intervals)	55	0.402			
A × B	5	0.045	0.417	0.835	0.037
Error(A × B)	55	0.109			

Table 6.11
ANOVA for colour swaps and shape swaps for each study-test interval in the randomized shapes condition in Experiment 6 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.402	3.110	0.106	0.220
Error(Swaps)	11	0.129			
Study-test intervals (B)	5	2.675	6.539	0.000	0.373
Error(Study-test intervals)	55	0.409			
A × B	5	0.114	0.713	0.616	0.061
Error(A × B)	55	0.160			

Table 6.12
ANOVA comparing Experiments 3 and 6

Source	df	MS	F	p	partial η^2
Between Subjects					
Experiment (A)	1	4.995	1.689	0.207	0.071
Error	22	2.957			
Within-Subjects					
Unchanged/Randomized (B)	1	18.150	29.582	0.000	0.573
A × B	1	0.135	0.220	0.644	0.010
Error(Unchanged/Randomized)	22	0.614			
Study-test interval (C)	3	5.572	14.085	0.000	0.390
Error(Study-test interval)	66	0.396			
A × C	5	0.625	2.617	0.028	0.106
Error(Study-test interval)	110	0.239			
B × C	5	9.189	46.140	0.000	0.677
A × B × C	5	0.351	1.762	0.127	0.074
Error(B × C)	110	0.199			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 6.13
d primes and beta for each study-test interval for unchanged and randomized colours in Experiment 7 (N=12)

Experiment 7	d'				beta			
Study-test interval	Unchanged colours		Randomized colours		Unchanged colours		Randomized colours	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.868	0.339	2.492	0.718	8.560	1.922	2.919	2.381
500 ms	2.544	0.515	1.667	0.636	5.276	2.938	1.865	0.714
1000 ms	1.980	0.489	1.699	0.511	3.226	3.056	2.753	2.495
1500 ms	1.754	0.654	1.858	0.761	2.994	2.583	2.954	3.141
2000 ms	1.745	0.596	1.542	0.553	2.751	2.672	2.376	1.568
2500 ms	1.513	0.701	1.516	0.632	2.892	2.652	2.476	2.326
Average	2.234	0.549	1.796	0.635	4.283	2.637	2.557	2.104

Table 6.14
ANOVA for each study-test interval for unchanged and randomized colours in Experiment 7 (N=12)

Source	df	MS	F	p	partial η²
Unchanged/Randomized (A)	1	6.916	15.504	0.002	0.585
Error(Unchanged/Randomized)	11	0.446			
Study-test intervals (B)	5	8.775	36.515	0.000	0.768
Error(Study-test intervals)	55	0.240			
A × B	5	1.965	15.728	0.000	0.588
Error(A × B)	55	0.125			

Table 6.15
d primes for colour swaps and shape swaps for each study-test interval for unchanged and randomized colours in Experiment 7 (N=12)

Experiment 7	Unchanged colours				Randomized colours			
Study-test interval	Location swap		Shape swap		Location swap		Shape swap	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.75	0.29	3.662	0.262	2.415	0.749	2.550	0.796
500 ms	2.743	0.586	2.418	0.568	1.806	0.777	1.575	0.593
1000 ms	2.129	0.696	1.892	0.441	1.677	0.467	1.804	0.796
1500 ms	1.794	0.757	1.732	0.572	1.807	0.751	1.935	0.823
2000 ms	1.77	0.726	1.812	0.743	1.564	0.628	1.538	0.586
2500 ms	1.614	0.631	1.462	0.825	1.696	0.615	1.390	0.773
Average	2.300	0.614	2.163	0.569	1.827	0.665	1.799	0.728

Table 6.16
ANOVA for colour swaps and shape swaps for each study-test interval in the unchanged colours condition in Experiment 7 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.676	6.669	0.025	0.377
Error(Swaps)	11	0.101			
Study-test intervals (B)	5	15.549	40.528	0.000	0.787
Error(Study-test intervals)	55	0.384			
A × B	5	0.103	0.684	0.637	0.059
Error(A × B)	55	0.150			

Table 6.17
ANOVA for colour swaps and shape swaps for each study-test interval in the randomized colours condition in Experiment 7 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.030	0.159	0.698	0.014
Error(Swaps)	11	0.187			
Study-test intervals (B)	5	2.944	8.371	0.000	0.432
Error(Study-test intervals)	55	0.352			
A × B	5	0.232	1.481	0.211	0.119
Error(A × B)	55	0.157			

Table 6.18
ANOVA comparing Experiments 4 and 7

Source	df	MS	F	p	partial η^2
Between Subjects					
Experiment (A)	1	7.625	3.245	0.085	0.129
Error	22	2.350			
Within-Subjects					
Unchanged/Randomized (B)	1	20.954	39.061	0.000	0.640
A × B	1	0.737	1.373	0.254	0.059
Error(Unchanged/Randomized)	22	0.536			
Study-test interval (C)	3	28.448	71.515	0.000	0.765
Error(Study-test interval)	68	0.398			
A × C	5	0.129	0.520	0.761	0.023
Error(Study-test interval)	110	0.248			
B × C	5	4.425	24.432	0.000	0.526
A × B × C	5	0.267	1.476	0.203	0.063
Error(B × C)	110	0.181			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 6.19
ANOVA comparing Experiments 5, 6, and 7

Source	df	MS	F	p	partial η^2
Between Subjects					
Experiment (A)	2	24.746	11.271	0.000	0.406
Error	33	2.195			
Within-Subjects					
Unchanged/Randomized (B)	1	38.096	62.499	0.000	0.654
A × B	2	2.286	3.750	0.034	0.185
Error(Unchanged/Randomized)	33	0.610			
Study-test interval (C)	3.64	14.377	52.279	0.000	0.613
Error(Study-test interval)	120.14	0.275			
A × C	10	1.428	7.132	0.000	0.302
Error(Study-test interval)	165	0.200			
B × C	3.63	19.187	88.270	0.000	0.728
Error(B × C)	119.88	0.217			
A × B × C	10	0.730	4.622	0.000	0.219
Error(A × B × C)	165	0.158			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 6.20
ANOVA comparing Experiments 5, 6, and 7 (Unchanged condition)

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	6.035	5.093	0.012	0.236
Error	33	1.185			
Within-Subjects					
Study-test intervals (B)	4	30.610	125.184	0.000	0.791
Error(Study-test intervals)	130	0.245			
A × B	10	0.511	2.645	0.005	0.138
Error(Study-test intervals)	165	0.193			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 6.21
ANOVA comparing Experiments 5, 6, and 7 (Randomized condition)

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	21	12.961	0.000	0.440	25.922
Error	2				
Within-Subjects					
Study-test intervals (B)	5	0.217	1.314	0.261	0.038
A × B	10	1.647	9.985	0.000	0.377
Error(Study-test intervals)	165	0.165			

APPENDIX D

TABLES FOR CHAPTER 7

Table 7.1
d primes and beta for each study-test interval for unchanged and randomized locations in Experiment 8 (N=12)

Experiment 8	d'				beta			
Study-test interval	Unchanged locations		Randomized locations		Unchanged locations		Randomized locations	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.156	0.498	0.574	0.375	6.578	0.854	1.140	0.223
500 ms	1.799	0.401	0.632	0.359	4.807	2.266	1.115	0.120
1000 ms	1.630	0.469	0.592	0.358	3.025	1.650	1.119	0.133
1500 ms	1.556	0.435	0.910	0.337	3.457	2.274	1.302	0.354
2000 ms	1.425	0.335	0.882	0.359	2.750	2.042	1.280	0.386
2500 ms	1.235	0.409	0.771	0.455	2.354	1.021	1.587	1.655
Average	1.800	0.424	0.727	0.374	3.829	1.684	1.257	0.478

Table 7.2
ANOVA for each study-test interval for unchanged and randomized locations in Experiment 8 (N=12)

Source	df	MS	F	p	partial η^2
Unchanged/Randomized (A)	1	41.472	208.196	0.000	0.950
Error(Unchanged/Randomized)	11	0.199			
Study-test intervals (B)	5	2.249	14.021	0.000	0.560
Error(Study-test intervals)	55	0.160			
A × B	5	3.745	35.666	0.000	0.764
Error(A × B)	55	0.105			

Table 7.3
d primes for colour swaps and shape swaps for each study-test interval for unchanged and randomized locations in Experiment 8 (N=12)

Experiment 8	Unchanged locations				Randomized locations			
Study-test interval	Colour swap		Shape swap		Colour swap		Shape swap	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 ms	3.049	0.602	3.137	0.43	0.585	0.361	0.562	0.504
500 ms	1.775	0.489	1.816	0.563	0.604	0.576	0.672	0.414
1000 ms	1.705	0.75	1.54	0.42	0.594	0.429	0.594	0.389
1500 ms	1.727	0.702	1.41	0.353	0.934	0.521	0.924	0.467
2000 ms	1.578	0.424	1.275	0.333	0.986	0.499	0.804	0.366
2500 ms	1.219	0.64	1.277	0.33	0.878	0.257	0.708	0.840
Average	1.842	0.601	1.742	0.405	0.764	0.440	0.711	0.496

Table 7.4
ANOVA for colour swaps and shape swaps for each study-test interval in the unchanged locations condition in Experiment 8 (N=12)

Source	df	MS	F	p	partial η^2
Swaps (A)	1	0.357	2.456	0.145	0.183
Error(Swaps)	11	0.146			
Study-test intervals (B)	5	10.567	35.582	0.000	0.764
Error(Study-test intervals)	55	0.297			
A × B	5	0.207	1.008	0.422	0.084
Error(A × B)	55	0.205			

Table 7.5
ANOVA for colour swaps and shape swaps for each study-test interval in the randomized locations condition in Experiment 8 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.314	0.998	0.339	0.083
Error(Swaps)	11	0.315			
Study-test intervals (B)	5	0.333	0.607	0.695	0.052
Error(Study-test intervals)	55	0.549			
A × B	5	0.369	2.579	0.036	0.190
Error(A × B)	55	0.143			

Table 7.6
ANOVA comparing Experiments 2, 5, and 8

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	0.020	0.026	0.975	0.002
Error	33	0.772			
Within-Subjects					
Unchanged/Randomized (B)	1	95.952	204.922	0.000	0.861
A × B	2	0.464	0.990	0.382	0.057
Error(Unchanged/Randomized)	33	0.468			
Study-test interval (C)	5	9.501	65.009	0.000	0.663
A × C	10	0.422	2.886	0.002	0.149
Error(Study-test interval)	165	0.146			
B × C	5	19.024	122.357	0.000	0.788
A × B × C	10	0.333	2.144	0.024	0.115
Error(B × C)	165	0.155			

Table 7.7
ANOVA comparing Experiments 2, 5, and 8 (Unchanged locations)

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	0.273	0.436	0.650	0.026
Error	33	0.627			
Within-Subjects					
Study-test intervals (B)	5	27.621	157.639	0.000	0.827
A × B	10	0.513	2.930	0.002	0.151
Error(Study-test intervals)	165	0.175			

Table 7.8
ANOVA comparing Experiments 2, 5, and 8 (Randomized locations)

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	0.210	0.343	0.712	0.020
Error	33	0.614			
Within-Subjects					
Study-test intervals (B)	5	0.904	7.149	0.000	0.178
A × B	10	0.242	1.913	0.047	0.104
Error(Study-test intervals)	165	0.126			

Table 7.9
d primes and beta for each study-test interval for unchanged and randomized locations in Experiment 9 (N=12)

Experiment 9	d'				beta			
Study-test interval	Unchanged locations		Randomized locations		Unchanged locations		Randomized locations	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
100 ms	1.423	0.603	0.553	0.295	4.721	2.383	1.147	0.226
500 ms	1.514	0.590	0.586	0.512	4.257	2.395	1.197	0.351
1000 ms	1.445	0.551	0.870	0.522	3.329	2.294	1.430	0.794
1500 ms	1.252	0.585	0.845	0.471	1.765	0.541	1.467	0.836
2000 ms	1.394	0.702	0.652	0.694	2.765	2.144	1.256	0.373
2500 ms	1.187	0.695	0.700	0.476	2.604	2.126	1.154	0.136
Average	1.369	0.621	0.701	0.495	3.240	1.980	1.275	0.453

Table 7.10
ANOVA for each study-test interval for unchanged and randomized locations in Experiment 9 (N=12)

Source	df	MS	F	p	partial η^2
Unchanged/Randomized (A)	1	16.067	46.401	0.000	0.808
Error(Unchanged/Randomized)	11	0.346			
Study-test intervals (B)	5	0.126	0.476	0.793	0.041
Error(Study-test intervals)	55	0.265			
A × B	5	0.269	1.226	0.309	0.100
Error(A × B)	55	0.219			

Table 7.11
d primes for colour swaps and shape swaps for each study-test interval for unchanged and randomized locations in Experiment 9 (N=12)

Experiment 9	Unchanged locations				Randomized locations			
Study-test interval	Colour swap		Shape swap		Colour swap		Shape swap	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
100 ms	1.278	0.514	1.567	0.751	0.507	0.324	0.623	0.490
500 ms	1.603	0.789	1.449	0.569	0.603	0.558	0.572	0.625
1000 ms	1.542	0.54	1.342	0.658	0.940	0.629	0.818	0.541
1500 ms	1.162	0.787	1.383	0.504	0.750	0.501	0.968	0.571
2000 ms	1.208	0.788	1.612	0.699	0.748	0.831	0.581	0.743
2500 ms	1.207	0.892	1.208	0.692	0.628	0.504	0.751	0.555
Average	1.333	0.718	1.427	0.645	0.696	0.558	0.719	0.587

Table 7.12
ANOVA for colour swaps and shape swaps for each study-test interval in the unchanged locations condition in Experiment 9 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.314	0.998	0.339	0.083
Error(Swaps)	11	0.315			
Study-test intervals (B)	5	0.333	0.607	0.695	0.052
Error(Study-test intervals)	55	0.549			
A × B	5	0.369	2.579	0.036	0.190
Error(A × B)	55	0.143			

Table 7.13
ANOVA for colour swaps and shape swaps for each study-test interval in the randomized locations condition in Experiment 9 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.020	0.236	0.637	0.021
Error(Swaps)	11	0.083			
Study-test intervals (B)	5	0.428	0.938	0.464	0.079
Error(Study-test intervals)	55	0.456			
A × B	5	0.140	0.838	0.528	0.071
Error(A × B)	55	0.167			

Table 7.14
d primes and beta for each study-test interval for unchanged and randomized locations in Experiment 10 (N=12)

Experiment 10	d'				beta			
Study-test interval	Unchanged locations		Randomized locations		Unchanged locations		Randomized locations	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
400 ms	1.710	0.580	1.307	0.541	4.147	2.445	2.234	1.650
500 ms	1.784	0.528	0.858	0.593	3.214	1.927	1.857	1.048
1000 ms	1.557	0.612	0.948	0.706	3.296	2.317	2.805	2.218
1500 ms	1.669	0.493	0.942	0.546	2.990	2.087	1.833	1.616
2000 ms	1.363	0.564	0.951	0.587	3.052	2.404	1.513	0.814
2500 ms	1.342	0.614	0.631	0.501	2.361	1.699	1.404	0.790
Average	1.571	0.565	0.939	0.579	3.177	2.146	1.941	1.356

Table 7.15
ANOVA for each study-test interval for unchanged and randomized locations in Experiment 10 (N=12)

Source	df	MS	F	p	partial η²
Unchanged/Randomized (A)	1	14.356	36.724	0.000	0.770
Error(Unchanged/Randomized)	11	0.391			
Study-test intervals (B)	5	0.733	3.585	0.007	0.246
Error(Study-test intervals)	55	0.205			
A × B	5	0.243	1.584	0.180	0.126
Error(A × B)	55	0.154			

Table 7.16
d primes for colour swaps and shape swaps for each study-test interval for unchanged and randomized locations in Experiment 10 (N=12)

Experiment 10	Unchanged locations				Randomized locations			
Study-test interval	Colour swap		Shape swap		Colour swap		Shape swap	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
400 ms	1.830	0.733	1.614	0.543	1.320	0.747	1.333	0.520
500 ms	1.736	0.708	1.854	0.462	0.966	0.503	0.761	0.747
1000 ms	1.609	0.573	1.511	0.733	0.919	0.743	0.976	0.797
1500 ms	1.819	0.564	1.54	0.524	1.149	0.685	0.794	0.708
2000 ms	1.401	0.629	1.331	0.614	1.004	0.711	0.914	0.567
2500 ms	1.375	0.667	1.335	0.65	0.430	0.566	0.860	0.671
Average	1.628	0.646	1.531	0.588	0.965	0.659	0.940	0.668

Table 7.17
ANOVA for colour swaps and shape swaps for each study-test interval in the unchanged locations condition in Experiment 10 (N=12)

Source	df	MS	F	p	partial η^2
Swaps (A)	1	0.341	2.912	0.116	0.209
Error(Swaps)	11	0.117			
Study-test intervals (B)	5	0.832	2.172	0.071	0.165
Error(Study-test intervals)	55	0.383			
A × B	5	0.117	0.898	0.489	0.075
Error(A × B)	55	0.131			

Table 7.18
ANOVA for colour swaps and shape swaps for each study-test interval in the randomized locations condition in Experiment 10 (N=12)

Source	df	MS	F	p	partial η^2
Swaps (A)	1	0.023	0.088	0.772	0.008
Error(Swaps)	11	0.257			
Study-test intervals (B)	1.849	3.157	3.389	0.057	0.236
Error(Study-test intervals)	20.344	0.932			
A × B	5	0.433	2.327	0.055	0.175
Error(A × B)	55	0.186			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 7.19
ANOVA comparing Experiments 8, 9, and 10

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	2.420	2.188	0.128	0.117
Error	33	1.106			
Within-Subjects					
Unchanged/Randomized (B)	1	67.566	216.470	0.000	0.868
A × B	2	2.165	6.935	0.003	0.296
Error(Unchanged/Randomized)	33	0.312			
Study-test interval (C)	3.788	2.301	8.298	0.000	0.201
Error(Study-test intervals)	125.008	0.277			
A × C	10	0.683	3.250	0.001	0.165
Error(Study-test interval)	165	0.210			
B × C	5	1.581	9.929	0.000	0.231
A × B × C	10	1.338	8.403	0.000	0.337
Error(B × C)	165	0.159			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 7.20
ANOVA comparing Experiments 8, 9, and 10 (Unchanged locations)

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	3.351	4.399	0.020	0.210
Error	33	0.762			
Within-Subjects					
Study-test intervals (B)	5	3.097	15.112	0.000	0.314
A × B	10	1.613	7.873	0.000	0.323
Error(Study-test intervals)	165	0.205			

Table 7.21
One way ANOVA comparing performance at the initial study test interval in Experiments 8, 9, and 10 (Unchanged locations)

Source	df	MS	F	p
Experiment	2	10.360	32.821	0.000
Error (Within)	33	0.316		

Table 7.22
3×5 ANOVA comparing performance at study-test intervals ranging from 500 to 2500 ms in Experiments 8, 9, and 10 (Unchanged locations)

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	0.635	0.851	0.436	0.049
Error	33	0.746			
Within-Subjects					
Study-test intervals (B)	4	0.994	5.486	0.000	0.143
A × B	8	0.106	0.584	0.790	0.034
Error(Study-test intervals)	132	0.181			

Table 7.23
ANOVA comparing Experiments 8, 9, and 10 (Randomized locations)

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	1.233	1.878	0.169	0.102
Error	33	0.656			
Within-Subjects					
Study-test intervals (B)	5	0.228	1.385	0.232	0.040
A × B	10	0.407	2.478	0.009	0.131
Error(Study-test intervals)	165	0.164			

Table 7.24
One way ANOVA comparing performance at the initial study test interval in Experiments 8, 9, and 10 (Randomized locations)

Source	df	MS	F	p
Experiment	2	2.212	12.752	0.000
Error (Within)	33	0.173		

Table 7.25
3×5 ANOVA comparing performance at study-test intervals ranging from 500 to 2500 ms in Experiments 8, 9, and 10 (Randomized locations)

Source	df	MS	F	p	partial η²
Between Subjects					
Experiment (A)	2	0.308	0.483	0.621	0.028
Error	33	0.638			
Within-Subjects					
Study-test intervals (B)	4	0.279	1.675	0.160	0.048
A × B	8	0.187	1.124	0.351	0.064
Error(Study-test intervals)	132	0.167			

APPENDIX E

TABLES FOR CHAPTER 8

Table 8.1

d primes and beta for each study-test interval and study-display duration for unchanged and randomized locations in Experiment 11 (N=12)

Experiment 11		d'				beta			
Study-test interval	Study-display duration	Unchanged locations		Randomized locations		Unchanged locations		Randomized locations	
(in ms)	(in ms)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	200	3.465	0.411	0.513	0.386	7.346	3.002	1.413	0.787
0	900	3.612	0.362	0.976	0.557	7.116	2.736	1.860	1.214
0	1500	3.664	0.394	0.896	0.394	6.011	2.981	1.434	0.580
2000	200	1.090	0.308	0.936	0.470	1.530	0.618	1.613	0.663
2000	900	1.154	0.628	0.945	0.428	1.621	0.792	1.577	0.587
2000	1500	1.429	0.495	1.314	0.655	1.611	0.772	2.614	2.533
Average		2.402	0.433	0.930	0.482	4.206	1.817	1.752	1.060

Table 8.2
ANOVA for Experiment 11 (N=12)

Source	df	MS	F	p	partial η²
Unchanged/Randomized (A)	1	78.056	726.058	0.000	0.985
Error(Unchanged/Randomized)	11	0.108			
Study-test intervals (B)	1	39.187	115.429	0.000	0.913
Error(Study-test intervals)	11	0.339			
Study-display durations (C)	2	1.266	8.444	0.002	0.434
Error(Study-display durations)	22	0.150			
A × B	1	62.071	214.424	0.000	0.951
Error(A × B)	11	0.289			
A × C	2	0.059	0.367	0.697	0.032
Error(A × C)	22	0.161			
B × C	2	0.379	2.245	0.130	0.170
Error(B × C)	22	0.169			
A × B × C	2	0.105	0.661	0.526	0.057
Error(A × B × C)	22	0.159			

Table 8.3
d primes for colour swaps and shape swaps for each study-test interval and each study display duration for unchanged and randomized locations in Experiment 11 (N=12)

Experiment 11		Unchanged locations				Randomized locations			
Study-test interval	Study-display duration	Colour swap		Shape swap		Colour swap		Shape swap	
(in ms)	(in ms)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	200	3.297	0.465	3.508	0.481	0.456	0.394	0.564	0.464
0	900	3.385	0.382	3.616	0.261	1.028	0.612	0.931	0.604
0	1500	3.361	0.351	3.582	0.47	0.900	0.369	0.902	0.505
2000	200	0.942	0.39	1.278	0.414	0.979	0.427	0.901	0.659
2000	900	1.334	0.901	1.028	0.53	1.030	0.661	0.889	0.322
2000	1500	1.524	0.572	1.352	0.578	1.374	0.753	1.292	0.742
Average		2.307	0.510	2.394	0.456	0.961	0.536	0.913	0.549

Table 8.4
ANOVA comparing colour swaps and shape swaps for each study-test interval and each study display duration for unchanged locations in Experiment 11 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.272	1.617	0.230	0.128
Error(Swaps)	11	0.168			
Study-test intervals (B)	1	176.646	243.773	0.000	0.957
Error(Study-test intervals)	11	0.725			
Study-display durations (C)	2	0.478	1.612	0.222	0.128
Error(Study-display durations)	22	0.297			
A × B	1	0.647	3.812	0.077	0.257
Error(A × B)	11	0.170			
A × C	2	0.325	2.426	0.112	0.181
Error(A × C)	22	0.134			
B × C	2	0.300	1.694	0.207	0.133
Error(B × C)	22	0.177			
A × B × C	2	0.362	3.025	0.069	0.216
Error(A × B × C)	22	0.120			

Table 8.5
ANOVA comparing colour swaps and shape swaps for each study-test interval and each study display duration for randomized locations in Experiment 11 (N=12)

Source	df	MS	F	p	partial η^2
Swaps (A)	1	0.083	1.837	0.202	0.143
Error(Swaps)	11	0.045			
Study-test intervals (B)	1	2.831	5.089	0.045	0.316
Error(Study-test intervals)	11	0.556			
Study-display durations (C)	2	1.878	6.283	0.007	0.364
Error(Study-display durations)	22	0.299			
A × B	1	0.098	0.816	0.386	0.069
Error(A × B)	11	0.120			
A × C	1.386	0.079	0.434	0.584	0.038
Error(A × C)	15.251	0.181			
B × C	2	0.813	1.713	0.204	0.135
Error(B × C)	22	0.475			
A × B × C	2	0.016	0.086	0.918	0.008
Error(A × B × C)	22	0.188			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 8.6
d primes and beta for each study-test interval and each study display duration for unchanged and randomized locations in Experiment 12 (N=12)

Experiment 12		d'				beta			
Study-test interval	Study-display duration	Unchanged locations		Randomized locations		Unchanged locations		Randomized locations	
(in ms)	(in ms)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	200	2.802	0.688	0.534	0.530	3.406	3.120	1.482	0.621
0	900	3.501	0.586	1.038	0.652	6.469	2.996	2.383	2.391
0	1500	3.490	0.572	0.998	0.536	6.720	3.255	1.913	0.830
2000	200	0.991	0.291	0.897	0.481	1.403	0.439	2.010	2.407
2000	900	1.231	0.525	1.130	0.574	2.241	2.401	2.370	1.519
2000	1500	1.160	0.472	0.997	0.597	1.794	1.180	2.020	1.289
Average		2.196	0.522	0.932	0.562	3.672	2.232	2.030	1.510

Table 8.7
ANOVA for Experiment 12 (N=12)

Source	df	MS	F	p	partial η²
Unchanged/Randomized (A)	1	57.477	101.460	0.000	0.902
Error(Unchanged/Randomized)	11	0.566			
Study-test intervals (B)	1	35.523	114.295	0.000	0.912
Error(Study-test intervals)	11	0.311			
Study-display durations (C)	2	2.447	15.958	0.000	0.592
Error(Study-display durations)	22	0.153			
A × B	1	47.131	133.661	0.000	0.924
Error(A × B)	11	0.353			
A × C	2	0.067	0.410	0.668	0.036
Error(A × C)	22	0.164			
B × C	2	0.667	3.978	0.034	0.266
Error(B × C)	22	0.168			
A × B × C	2	0.031	0.288	0.753	0.025
Error(A × B × C)	22	0.106			

Table 8.8
d primes for colour swaps and shape swaps for each study-test interval and each study display duration for unchanged and randomized locations in Experiment 12 (N=12)

Experiment 12		Unchanged locations				Randomized locations			
Study-test interval	Study-display duration	Colour swap		Shape swap		Colour swap		Shape swap	
(in ms)	(in ms)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	200	2.504	0.732	2.979	0.573	0.494	0.495	0.591	0.702
0	900	3.261	0.554	3.536	0.43	0.974	0.683	1.102	0.656
0	1500	3.27	0.52	3.491	0.54	1.059	0.536	0.940	0.644
2000	200	0.931	0.477	1.124	0.503	0.871	0.519	0.937	0.591
2000	900	1.347	0.578	1.165	0.643	1.222	0.633	1.047	0.601
2000	1500	1.121	0.573	1.198	0.569	0.956	0.705	1.045	0.547
Average		2.072	0.572	2.249	0.543	0.929	0.595	0.944	0.624

Table 8.9
ANOVA comparing colour swaps and shape swaps for each study-test interval and each study display duration for unchanged locations in Experiment 12 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	1.123	4.224	0.064	0.277
Error(Swaps)	11	0.266			
Study-test intervals (B)	1	147.744	149.667	0.000	0.932
Error(Study-test intervals)	11	0.987			
Study-display durations (C)	2	2.781	6.930	0.005	0.386
Error(Study-display durations)	22	0.401			
A × B	1	0.778	3.332	0.095	0.232
Error(A × B)	11	0.234			
A × C	2	0.255	2.482	0.107	0.184
Error(A × C)	22	0.103			
B × C	2	0.895	3.451	0.050	0.239
Error(B × C)	22	0.259			
A × B × C	2	0.074	0.688	0.513	0.059
Error(A × B × C)	22	0.108			

Table 8.10
ANOVA comparing colour swaps and shape swaps for each study-test interval and each study display duration for randomized locations in Experiment 12 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.007	0.065	0.803	0.006
Error(Swaps)	11	0.113			
Study-test intervals (B)	1	0.842	5.073	0.046	0.316
Error(Study-test intervals)	11	0.166			
Study-display durations (C)	1.292	2.673	8.321	0.008	0.431
Error(Study-display durations)	14.217	0.321			
A × B	1	0.016	0.141	0.715	0.013
Error(A × B)	11	0.115			
A × C	2	0.041	0.321	0.729	0.028
Error(A × C)	22	0.127			
B × C	2	0.420	1.598	0.225	0.127
Error(B × C)	22	0.263			
A × B × C	2	0.194	2.363	0.118	0.177
Error(A × B × C)	22	0.082			
Underlined df indicates value after applying Greenhouse Geisser correction					

Table 8.11
d primes for four categories of swaps for each independent variable in Experiment 12 (N=12)

Experiment 12 - d'		Swap stimuli							
		1 and 6		1 and 2,3,4,5		among 2,3,4,5		6 and 2,3,4,5	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Locations	Unchanged	2.120	0.562	1.897	0.253	1.764	0.186	1.897	0.317
	Randomized	1.367	0.834	1.062	0.595	0.779	0.469	0.859	0.499
Study-test interval	0 ms	2.132	0.676	1.849	0.417	1.614	0.323	1.627	0.366
	2000 ms	1.302	0.592	1.070	0.390	0.904	0.272	1.086	0.319
Study-display duration	200 ms	1.442	0.924	1.372	0.381	0.943	0.238	1.100	0.253
	900 ms	1.962	0.608	1.487	0.546	1.458	0.404	1.522	0.427
	1500 ms	1.668	0.470	1.409	0.353	1.345	0.353	1.438	0.405

Table 8.12
d primes and beta for each study-test interval and each study display duration for unchanged and randomized locations in Experiment 13 (N=12)

Experiment 13		d'				beta			
Study-test interval	Study-display duration	Unchanged locations		Randomized locations		Unchanged locations		Randomized locations	
(in ms)	(in ms)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	200	0.847	0.465	0.202	0.373	1.419	0.638	1.192	0.187
0	900	0.959	0.358	0.706	0.501	1.807	0.535	1.630	0.389
0	1500	1.026	0.542	0.874	0.410	1.964	1.217	1.629	0.612
2000	200	1.044	0.430	1.004	0.523	1.717	0.525	2.292	2.352
2000	900	0.954	0.553	0.843	0.437	2.106	2.433	1.359	0.336
2000	1500	0.902	0.361	0.735	0.451	1.551	0.597	1.402	0.578
Average		0.955	0.451	0.727	0.449	1.761	0.991	1.584	0.742

Table 8.13
ANOVA for Experiment 13 (N=12)

Source	df	MS	F	p	partial η^2
Unchanged/Randomized (A)	1	1.873	5.133	0.045	0.318
Error(Unchanged/Randomized)	11	0.365			
Study-test intervals (B)	1	0.755	3.485	0.089	0.241
Error(Study-test intervals)	11	0.217			
Study-display durations (C)	2	0.165	1.012	0.380	0.084
Error(Study-display durations)	22	0.163			
A × B	1	0.535	7.424	0.020	0.403
Error(A × B)	11	0.072			
A × C	1	0.178	0.689	0.461	0.059
Error(A × C)	15	0.258			
B × C	1	2.075	16.721	0.001	0.603
Error(B × C)	13	0.124			
A × B × C	2	0.312	2.022	0.156	0.155
Error(A × B × C)	22	0.154			
Underlined df indicates that Greenhouse Geisser correction was applied					

Table 8.14
d primes for colour swaps and shape swaps for each study-test interval and each study display duration for unchanged and randomized locations in Experiment 13 (N=12)

Experiment 13		Unchanged locations				Randomized locations			
Study-test interval	Study-display duration	Colour swap		Shape swap		Colour swap		Shape swap	
(in ms)	(in ms)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	200	0.787	0.541	0.93	0.602	0.192	0.571	0.194	0.317
0	900	0.981	0.432	0.933	0.38	0.660	0.622	0.740	0.546
0	1500	1.076	0.588	0.975	0.563	0.862	0.477	0.891	0.411
2000	200	1.117	0.4	0.984	0.625	1.012	0.579	0.998	0.582
2000	900	0.874	0.579	1.054	0.61	0.834	0.483	0.860	0.505
2000	1500	1.034	0.454	0.779	0.383	0.800	0.512	0.679	0.509
Average		0.978	0.499	0.943	0.527	0.727	0.541	0.727	0.478

Table 8.15
ANOVA comparing colour swaps and shape swaps for each study-test interval and each study display duration for unchanged locations in Experiment 13 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.045	0.490	0.498	0.043
Error(Swaps)	11	0.092			
Study-test intervals (B)	1	0.026	0.191	0.670	0.017
Error(Study-test intervals)	11	0.134			
Study-display durations (C)	2	0.002	0.005	0.995	0.000
Error(Study-display durations)	22	0.318			
A × B	1	0.041	0.390	0.545	0.034
Error(A × B)	11	0.104			
A × C	2	0.194	1.719	0.202	0.135
Error(A × C)	22	0.113			
B × C	2	0.294	0.997	0.385	0.083
Error(B × C)	22	0.295			
A × B × C	2	0.207	1.599	0.225	0.127
Error(A × B × C)	22	0.129			

Table 8.16
ANOVA comparing colour swaps and shape swaps for each study-test interval and each study display duration for randomized locations in Experiment 13 (N=12)

Source	df	MS	F	p	partial η²
Swaps (A)	1	0.000	0.000	0.997	0.000
Error(Swaps)	11	0.100			
Study-test intervals (B)	1	2.706	6.234	0.030	0.362
Error(Study-test intervals)	11	0.434			
Study-display durations (C)	2	0.602	1.602	0.224	0.127
Error(Study-display durations)	22	0.376			
A × B	1	0.048	0.298	0.596	0.026
Error(A × B)	11	0.163			
A × C	2	0.030	0.256	0.776	0.023
Error(A × C)	22	0.117			
B × C	2	2.845	16.728	0.000	0.603
Error(B × C)	22	0.170			
A × B × C	2	0.014	0.144	0.866	0.013
Error(A × B × C)	22	0.099			

Table 8.17
d primes for four categories of swaps for each independent variable in Experiment 13 (N=12)

Experiment 13 - d'		Swap stimuli							
		1 and 6		1 and 2,3,4,5		among 2,3,4,5		6 and 2,3,4,5	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Locations	Unchanged	1.648	0.441	1.033	0.535	0.667	0.279	1.044	0.342
	Randomized	1.155	0.462	0.820	0.430	0.558	0.332	0.714	0.256
Study-test intervals	0 ms	1.302	0.590	1.042	0.527	0.550	0.326	0.571	0.331
	2000 ms	1.466	0.295	0.813	0.391	0.642	0.278	1.227	0.262
Study-display durations	200 ms	1.033	0.558	0.718	0.427	0.673	0.241	0.828	0.331
	900 ms	1.662	0.648	1.094	0.467	0.604	0.337	0.757	0.300
	1500 ms	1.501	0.313	1.059	0.597	0.584	0.391	1.056	0.381

Table 8.18
d primes for four categories of swaps for each independent variable in Experiment 14 (N=12)

Experiment 14 - d'		Swap stimuli							
Study-test interval	Study-display duration	1 and 6		1 and 2,3,4,5		among 2,3,4,5		6 and 2,3,4,5	
(in ms)	(in ms)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	200	0.755	1.149	0.582	0.452	0.355	0.340	0.114	0.374
0	900	1.001	1.793	0.760	0.828	0.749	0.419	0.795	0.553
0	1500	1.048	0.433	0.744	0.829	0.577	0.733	0.940	0.758
2000	200	1.201	0.805	0.795	0.314	0.968	0.456	1.382	0.344
2000	900	2.504	1.054	0.945	0.562	0.779	0.539	1.244	0.669
2000	1500	1.867	0.982	0.973	0.650	0.901	0.613	1.274	0.786
Average		1.396	1.036	0.800	0.606	0.721	0.517	0.958	0.581

Table 8.19
ANOVA for Experiment 14 with all categories of swaps (N=12)

Source	df	MS	F	p	partial η²
Study-display duration (A)	2	2.953	3.715	0.041	0.252
Error	22	0.795			
Study-test intervals (B)	1	20.564	13.367	0.004	0.549
Error	11	1.538			
Swaps(C)	3	6.542	9.347	0.000	0.459
Error	33	0.700			
A × B	2	0.261	0.284	0.755	0.025
Error(A × B)	22	0.918			
A × C	3.000	1.230	0.912	0.446	0.077
Error(A × C)	32.995	1.348			
B × C	3	1.942	4.782	0.007	0.303
Error(B × C)	33	0.406			
A × B × C	2.570	2.747	1.851	0.167	0.144
Error(A × B × C)	28.268	1.484			
Underlined df indicates Greenhouse Geisser correction was applied					

Table 8.20
ANOVA for Experiment 14 with swaps of 1 and 6 deleted (N=12)

Source	df	MS	F	p	partial η²
Study-display duration (A)	2	0.884	2.136	0.142	0.163
Error	22	0.414			
Study-test intervals (B)	1	8.862	10.874	0.007	0.497
Error	11	0.815			
Swaps(C)	1.364	1.533	1.506	0.248	0.120
Error	15.004	1.018			
A × B	1.201	1.969	1.811	0.203	0.141
Error(A × B)	13.211	1.087			
A × C	4	0.125	0.467	0.760	0.041
Error(A × C)	44	0.267			
B × C	2	1.106	3.696	0.041	0.251
Error(B × C)	22	0.299			
A × B × C	4	0.443	2.718	0.042	0.198
Error(A × B × C)	44	0.163			
Underlined df indicates Greenhouse Geisser correction was applied					

Table 8.15

ANOVA comparing Experiments 11, 12, and 13

Source	df	MS	F	p	partial η^2
Between Subjects					
Experiment (A)	2	29.118	34.262	0.000	0.675
Error	33	0.850			
Within-Subjects					
Unchanged/Randomized (B)	1	105.433	304.469	0.000	0.902
A × B	2	15.986	46.166	0.000	0.737
Error(Unchanged/Randomized)	33	0.346			
Study-test intervals (C)	1	42.950	148.637	0.000	0.818
A × C	2	16.257	56.261	0.000	0.773
Error(Study-test intervals)	33	0.289			
Study-display duration (D)	2	2.931	18.846	0.000	0.364
A × D	4	0.474	3.044	0.023	0.156
Error(Study-display duration)	66	0.156			
B × C	1	79.827	335.328	0.000	0.910
A × B × C	2	14.955	62.820	0.000	0.792
Error(B × C)	33	0.238			
B × D	1.613	0.049	0.237	0.742	0.007
Error (B × D)	53.235	0.205			
A × B × D	4	0.103	0.621	0.649	0.036
Error(B × D)	66	0.166			
C × D	2	1.433	10.454	0.000	0.241
A × C × D	4	0.431	3.146	0.020	0.160
Error(C × D)	66	0.137			
B × C × D	2	0.131	0.939	0.396	0.028
A × B × C × D	4	0.158	1.130	0.350	0.064
Error(B × C × D)	66	0.140			

Underlined df indicates value after applying Greenhouse Geisser correction