PRIFYSGOL
BANGOR
UNIVERSITY

The experiential and neurological underpinnings of spatial working memory representations

Mohammad Zia Ul Haq Katshu

Thesis submitted to the School of Psychology, Bangor University in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Bangor, United Kingdom
May 2016

Acknowledgements

This work has come to fruition due to the direct and indirect contributions of many people. First of all, I would like to express my sincere gratitude to my supervisor, Giovanni d'Avossa, for his continuous support and guidance. I am especially indebted to him for his unrelenting pursuit to get to the heart of the problem and the countless thought provoking discussions we had during the completion of this work. I am also thankful to my second supervisors, initially Kimron Shapiro and later Paul Downing, and the PhD committee chair, Stephan Boehm, for their suggestions that have helped shape this work.

My thanks go to the past and present members of d'Avossa and Sapir lab - Ayelet Sapir, Jodie Butler, Bridget Andrews, Katherine Burnett and Alex Close for their feedback at different stages of my research. A special thank you to Neil Dundon for his contribution to collecting and analysing some of the data and for the stimulating discussions.

I am grateful to all the participants and undergraduate students who made this research possible; and my friends, Ashish and Mohan, who supported me in ways they could.

Finally, I would like to thank my wife, Indu, for always being there; my parents for believing in me; my sister, Ruby, and my lovely nieces, Fatima and Zainab, for reminding me to complete this work; and my son, Arsh, whose arrival gave the final push to complete this work.

Nottingham, May 2016

Contents

Abstract

It remains contentious how information is stored in visual working memory (vWM), even though it is well established that its capacity is limited. Most models have assumed that information is stored in representations that generalise over features. Distinct features and objects have also been assumed to be stored independent of each other. I will present evidence in this thesis that the precision of spatial recall is not only influenced by the number of objects held in memory, but also their location. Moreover, the configuration of the sample array affects recall of single items, suggesting that vWM depends on both, high-resolution local maps and coarse global, representations.

Various strategies may be available to overcome the limited capacity of vWM, for example, by utilizing information in long-term memory (LTM). I will demonstrate that recall is improved when spatial data are encoded in vWM using landmarks stored in LTM, but not visible at the time of encoding. On the other hand, statistical regularities in the distribution of the memorised objects' locations do not seem to affect recall. Sleep, known to consolidate LTM, has recently been suggested to improve vWM capacity as well. I will present evidence to show that immediate post-learning sleep plays a crucial role in improving vWM recall by consolidating landmarks in LTM, without improving overall vWM capacity.

vWM depends on a distributed cortical network including Visual, Parietal, Frontal and medial Occipito-Temporal areas, though the precise functional role of each area is yet to be established. I will show that binding spatial to visual features, e.g. location and colour, but not binding non-spatial features, is impaired in a patient with bilateral Lingual gyrus and Parahippocampal cortical lesions. Moreover, these lesions disproportionately affect the maintenance of high-resolution spatial data, but not the binding errors, in vWM over longer delays.

List of figures

List of tables

Abbreviations

WM – Working memory

vWM – Visual working memory

STM – Short-term memory

LTM – Long-term memory

SWS – Slow wave sleep

REM – Rapid eye movement

BOLD – Blood-oxygen-level dependent

fMRI – Functional magnetic resonance imaging

PET – Positron emission tomography

CDA – Contralateral delay activity

MVPA – Multi-voxel pattern analysis

MTL – Medial Temporal lobe

mOTC – medial Occipito-Temporal cortex

PHC - Parahippocampus

Publishing note

Chapter 2 has been published in PlosOne.
DOI:http://dx.doi.org/10.1371/journal.pone.0107969.

The abstract of Chapter 3 has been published in a special edition of Lancet reporting the proceedings of the Academy of Medical Sciences Spring Meeting.
DOI:http://dx.doi.org/10.1016/S0140-6736(16)00445-1

Chapters 3 and 4 are at different stages of publication process.

Chapter 1: General introduction

We live surrounded by objects, which vary on a scale that goes from the subatomic to the cosmic. An effective interaction with our environment requires an understanding of the scene layout as well as structure of surrounding objects. Simple day-to-day gestures and activities like lifting a cup of tea, walking across a living room or driving to work would be effortful without comprehending the spatial organisation of our surroundings. Now imagine walking into a new office and looking around the complex array of objects and their layout; close your eyes and you can barely walk a step or two before bumping into something. This demonstrates that our ability to precisely remember locations of single items within a novel scene is actually quite poor, even though our impression of the overall organization of the scene may be quite vivid. This memory limitation is not exclusive to spatial data, but generalises to other object features, like colour, shape, size and orientation. In fact, limited memory capacity is usually demonstrated by diminishing recall precision in the face of increasing memory load and appears to be universal across sensory modalities. Indeed, no counterexample has been provided so far of features whose short-tem memory (STM) recall is not subject to capacity limitations. Baddeley and Hitch (1974) expanded and framed this system of temporary storage, named working memory (WM) by Miller, Galanter and Pribram (1960), and suggested that its main purpose is to manipulate information in a goal directed fashion.

1.1 Working Memory

1.1.1 Working memory: A limited capacity multicomponent system

Baddeley and Hitch (1974) proposed that the system used to temporarily store and process information consists of a central executive and two independent storage buffers, including phonological loop and visuospatial sketchpad (Fig.

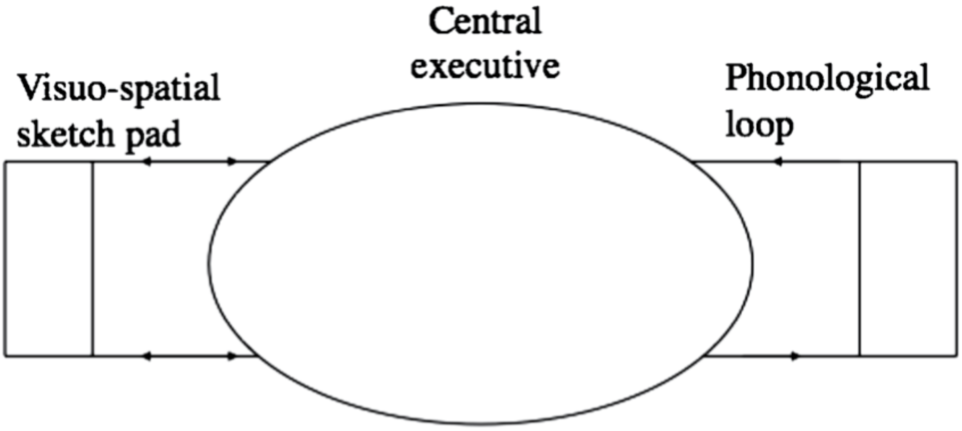

Figure 1.1: *The original model of working memory proposed by Baddeley and Hitch (1974) consisting of a central executive and two storage buffers - phonological loop and visuospatial sketchpad. This figure was adopted from Baddeley (2012) with permission from Annual Reviews.*

1.1). The central executive was also viewed as subject to processing limitations and was eventually conceived as an attentional system, which allows focussing, dividing and switching attention depending on the task demands (Baddeley, 1996). The phonological loop comprises a system for storing auditory information and an articulatory rehearsal process to refresh the memory trace (Baddeley & Larsen, 2007). The visuospatial sketchpad contains separate stores for visual features, like colour, shape, etc. and spatial information. It has also been proposed to have a rehearsal system, the inner scribe, analogous to the articulatory rehearsal of phonological loop (Logie, 2011). More recently, additional storage systems have been proposed to exist for other sensory modalities including haptic, gustatory and olfactory (Baddeley, 2012) (Fig. 1.2). Moreover, features belonging to different visual dimensions like colour, orientation, etc., may use different stores ensuring that only features belonging to the same dimension compete for limited resources in WM (Wheeler & Treisman, 2002). However, this view depends on the nature of the limitations that characterise WM. This has been hotly debated recently among proponents of two different theoretical models of WM – the slots and the resources models

(Bays & Husain, 2008; Luck & Vogel, 1997; Zhang & Luck, 2008).

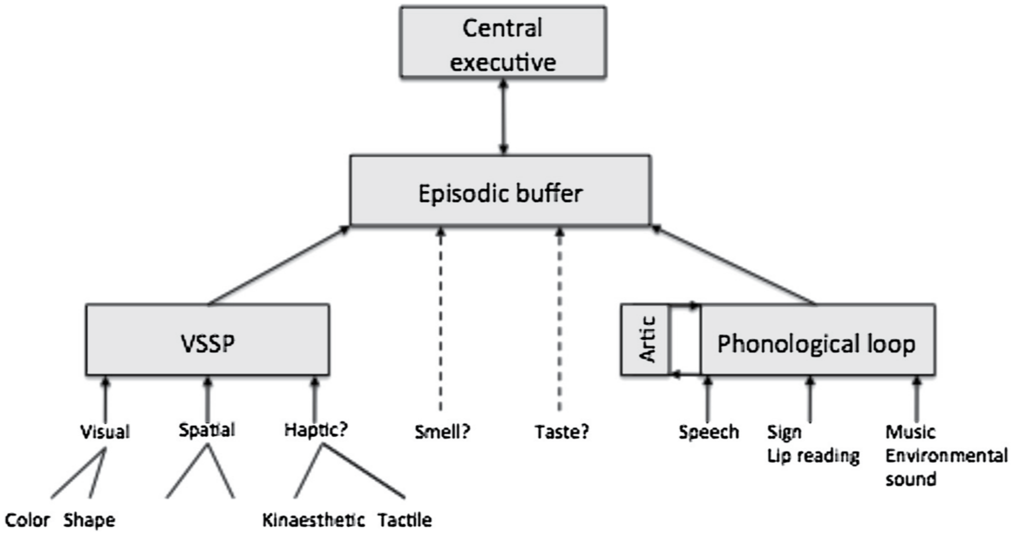

Figure 1.2: *Proposal for an extended working memory model incorporating storage buffers of other sensory modalities, like touch, smell and taste, besides visual and auditory by Baddeley (2012). VSSP – visuospatial sketchpad. This figure was adopted from Baddeley (2012) with permission from Annual Reviews.*

1.1.2 Fixed number of finite resolution slots limits the visual working memory capacity

Traditionally, studies of WM focussed on verbal information and assessed recall of lists of digits, letters or words (Waters & Caplan, 2003). An implicit assumption in many of these studies is that WM representations are object based. In the last two decades, there has been a surge of interest in exploring the nature of representations in visual working memory (vWM). Early vWM studies used a change detection paradigm, which assessed the ability to detect a single feature change, after a brief delay. The ability to detect a change was found to decline steeply once the sample scene contained more than three or four objects, irrespective of the objects' visual complexity (Fig. 1.3). These

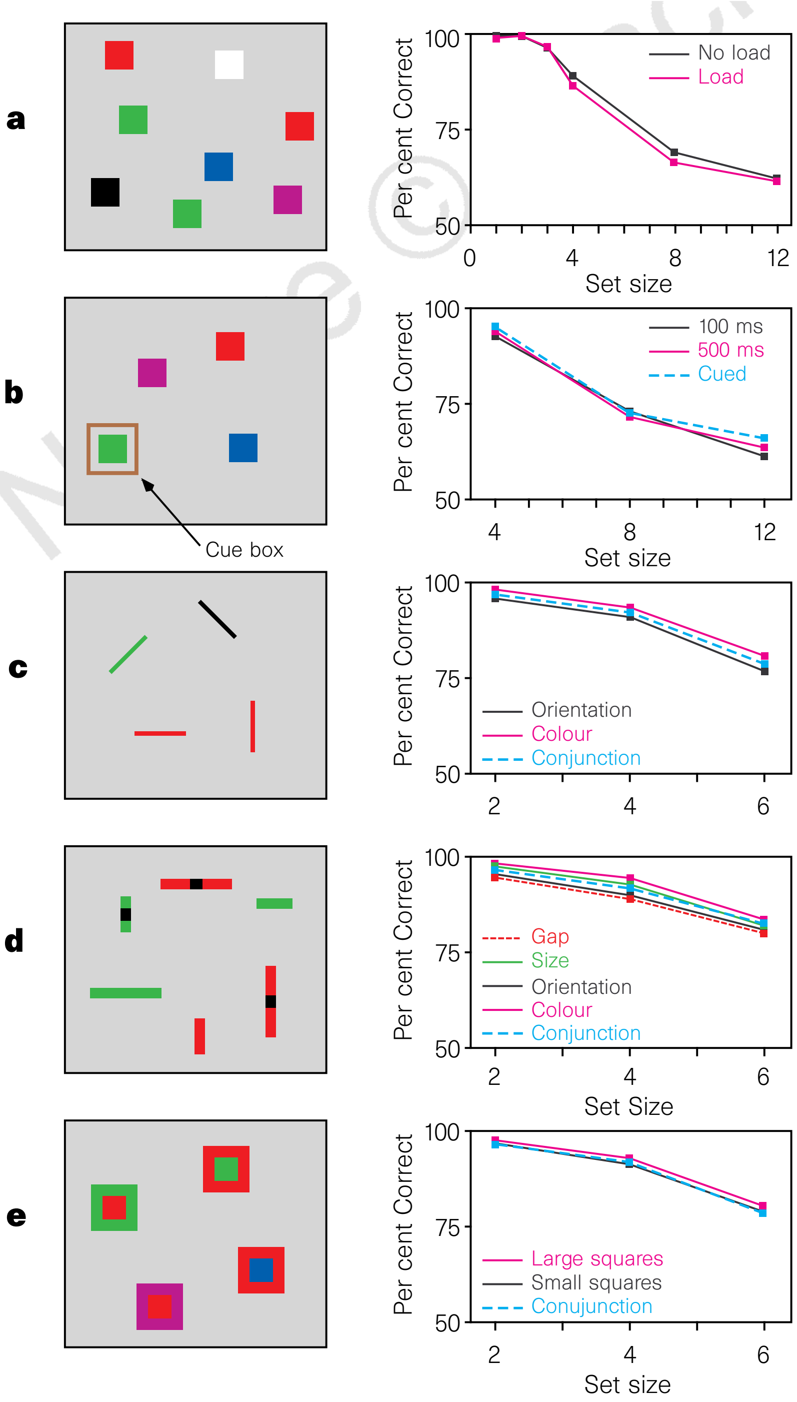

Figure 1.3: *Assessment of working memory (WM) capacity using change detection paradigm by Luck and Vogel (1997). a) Significant drop in WM performance after 3-4 objects for simple colour recall with and without verbal load. b) Comparison of 100ms and 500ms sample array presentation times showed no difference in WM performance. c) WM performance showed no difference whether the participants had to*

remember only colour or orientation or both. d) WM performance showed no difference whether the participants had to remember only one feature like presence or absence of gap in the stimulus, size, colour, or orientation or all the four features. e) WM performance showed no difference whether participants had to remember the colour of only large or small square or both the colours. This figure was adopted from Luck and Vogel (1997) with permission from Nature Publishing Group.

results were taken to imply that vWM capacity is limited to three to four slots of unlimited resolution, which accommodate as many objects, irrespective of the number of features to be remembered (Luck & Vogel, 1997). The slots model has some broad implications. First, while the number of objects that can be stored is limited, there are no limitations, per se, to the capacity to store features of an object and, therefore, complex objects should be recalled as well as simple ones. Secondly, different features belonging to the same object are automatically bound together, obviating the need to actively bind features together. Later, paradigms based on recall rather than recognition, showed that recall precision for individual features decreases even when two rather than one feature is stored in memory (Bays & Husain, 2008) (Fig. 1.4). To accommodate these findings, the slots model was updated: it was suggested that there are a fixed number of slots, each endowed with a finite resolution. Thus, when the number of objects to be stored is less than the number of slots, separate slots could be used to store information about the same object and improve recall by averaging (Zhang & Luck, 2008).

1.1.3 Flexible resource constraints vWM resolution

Recently, an alternative proposal has been put forth to account for load-dependent decrements in recall precision (Bays & Husain, 2008). This model suggests that a limited resource, rather than limited number of slots, is used to represent features in vWM. This resource can be flexibly allocated depending on the number of features. As the number of features to be remembered

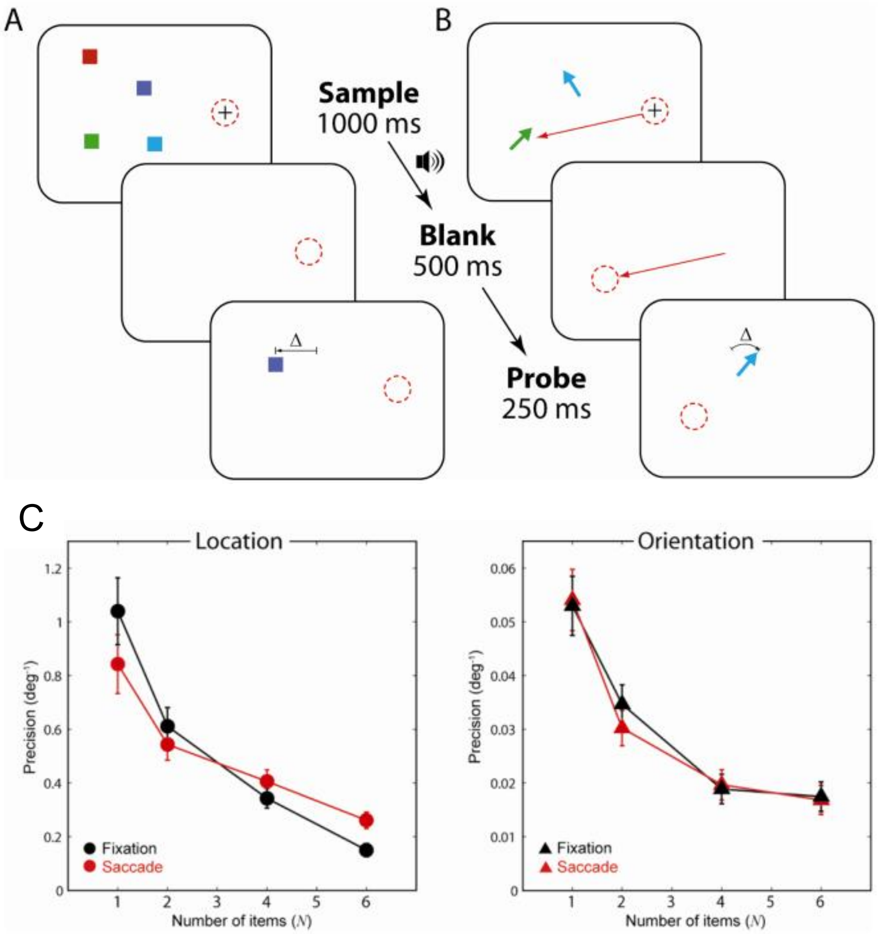

Figure 1.4: *Assessment of working memory capacity by discrimination-based task by Bays and Husain (2008). A) At probe, participants reported the direction of displacement of one of the objects in the sample array; the possible degrees of rightward or leftward displacement were 0.5^0, 2^0 and 5^0. B) At probe, participants reported the rotation of one of the objects in the sample array; the possible degrees of clockwise or anticlockwise rotation were 5^0, 20^0 ND 45^0. C) Continuous drop in precision, measured as the reciprocal of the standard deviation, is reported as the number of objects to be memorised increased; indeed maximum decrease in precision is noted when memory load increased from one to two. This figure was adopted and modified from Bays and Husain (2008) with permission from the American Association for the Advancement of Science (AAAS).*

increases, a smaller fraction of the resource is available to represent each feature, resulting in a decrease in precision. Unlike the slots model, the resource model does not place a limit on the number of features that can be stored, but predicts that recall precision should decrease as the memory load, i.e. the number of features, is increased. Additionally, this model does not preclude the possibility that binding errors are made in recall, since different features of the same object are presumed to be stored in independent representations. Moreover, an increase in the salience or task relevance of a feature has been shown to improve its recall precision; a finding that is difficult to reconcile with the slots model (Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011; Bays & Husain, 2008). On the other hand, flexible-resource idea can accommodate this finding, if one assumes that a greater share of the resource can be allocated to highly salient, task- relevant features.

1.1.4 Limitations of contemporary WM proposals

Sensory representations in visual cortex are tuned to specific features of the stimuli within a dimension, like specific colour, orientation or location (Hubel & Wiesel, 1974; Schiller, 2010; Smith, Singh, Williams, & Greenlee, 2001). In contrast, both fixed-slots and flexible-resource models assume that vWM representations are not tuned to specific features within a dimension. This would imply that the precision with which a feature is represented is independent of the specific feature value, be it the particular location, colour or orientation. This assumption may not be entirely consistent with recent functional imaging data, which showed that during the delay-period of a WM task, voxel-wise patterns of blood-oxygen-level dependent (BOLD) activity in retinotopic Visual areas V1-V4 carried task-relevant information about the memorised visual stimuli. Additionally, the delay-period activity was similar to activity evoked by task-irrelevant orientated stimuli (Serences, Ester, Vogel, & Awh, 2009). These findings suggest a fundamental homology between perceptual and WM representations in low-level Visual cortical areas, which contemporary WM models fail to accommodate.

Both the slots and flexible-resource models assume that features belonging to different objects are stored independently. However, change detection paradigms have shown that access to configurational information improves recognition accuracy (Jiang, Olson, & Chun, 2000). More crucially, recall based paradigms have shown that the recalled size of a circle is biased toward the mean size of the circles in the sample display (Brady & Alvarez, 2011). One mechanism to explain the effect of non-targets on target recall is that WM stores a summary statistic of the scene, besides information about single items. These ensemble statistics are known to be readily available perceptually for size, number, orientation and spatial frequency (Chong & Treisman, 2005; Girshick, Landy, & Simoncelli, 2011; Huang & Sekuler, 2010; Marchant, Simons, & de Fockert, 2013).

The effect of memory load on neural signals during the maintenance phase is considered to be the signature of WM related neural activity. A sustained negative change in voltage during the maintenance phase on the side contralateral, compared to the ipsilateral, to the memorised targets has been observed over the Parietal and Occipital electrodes. Crucially, this Contralateral Delay Activity (CDA) increases with memory load but reaches an asymptote around the WM capacity limits not only at the group but also at the individual level (Vogel & Machizawa, 2004; Vogel, McCollough, & Machizawa, 2005). Similar effects have been observed in functional magnetic resonance imaging (fMRI) studies showing an increase in BOLD signals in the posterior Parietal cortex with increase in memory load before reaching an asymptote around the individual's WM capacity limits (Todd & Marois, 2004, 2005). The initial version of the slots model explained the memory load dependence of neurophysiological signals nicely. Each object was supposed to occupy only one slot and as the number of objects to be memorised increased more slots would be taken up till no more slots were available. However, the modified version of slots proposal, the slots-averaging model, as well as the resource model posit that all of the slots or resource are taken up each time, irrespective of the memory load. Both these models, therefore, fail to account for the neurophysiological data.

1.2 Improving WM capacity

WM capacity strongly correlates with performance in a number of tasks probing different cognitive domains (Daneman & Merikle, 1996; Kyllonen & Christal, 1990). It is also one of the best predictors of fluid intelligence (Engle, Tuholski, Laughlin, & Conway, 1999). However, because WM capacity is limited and poses significant constraints on recall of task-relevant information, not surprisingly, various methods have evolved or have been devised to improve WM capacity (von Bastian & Oberauer, 2013). Here we will focus on two such strategies: the effect of long-term memory (LTM) and sleep on WM.

1.2.1 Interactions between WM and LTM

The capacity to recall is greater for semantically related than unrelated words (Poirier, Dhir, Tehan, & Hampton, 2011). This improved capacity to store information is understood to be the result of interaction between working and long-term semantic memory. Semantic information from LTM provides an obvious way to integrate the words in a meaningful sentence, thereby improving recall. To account for the interactions between different WM buffers, perception and LTM, Baddeley (2000) added another component, the episodic buffer, to the WM model. The episodic buffer binds information from different dimensionally-specific and modality-specific buffers and integrates perceptual and WM data as well as data in LTM and WM (Fig. 1.5). However, how this interaction between LTM and WM comes about is not entirely clear. Historically, the main technique to improve WM performance was based on exploiting imagery. This was done by substituting the information to be memorised with

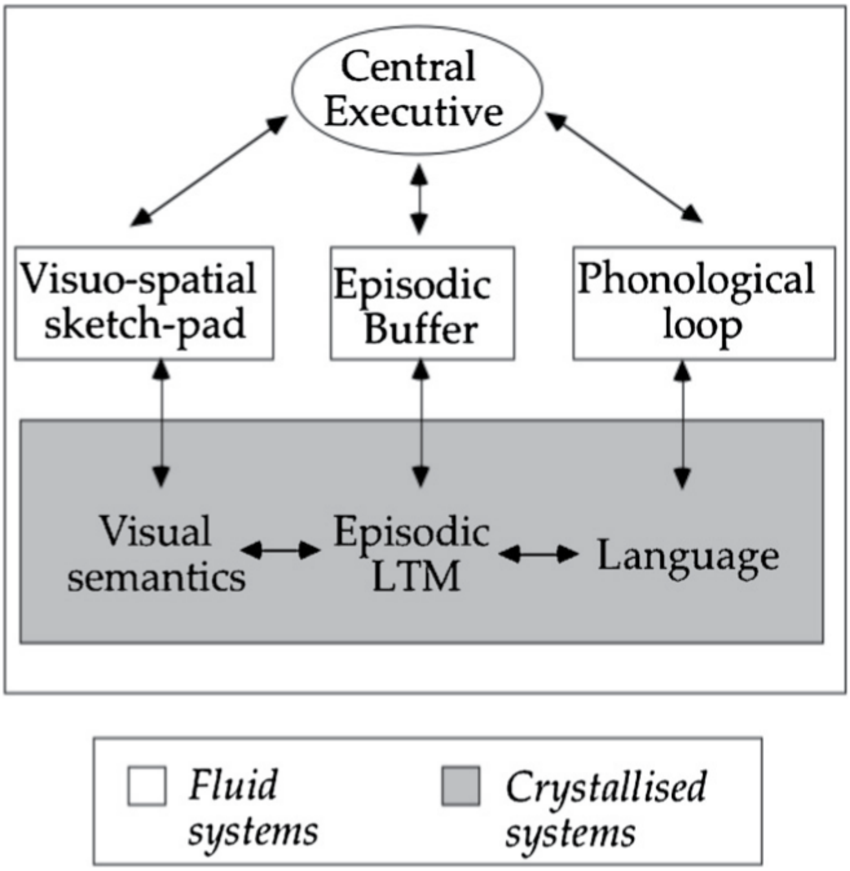

Figure 1.5: *Modified model of working memory after the introduction of episodic buffer by Baddeley (2000). LTM – long-term memory. This figure was adopted from Baddeley (2012) with permission from Annual Reviews.*

highly salient icons, whose recall was facilitated by their fantastic or grotesque nature, but whose symbolism was transparent to the mnenomist. The orderly and exhaustive recall of the icons was ensured by placing them in the halls and rooms of overlearnt memory palaces. The mnemonist would then be able to recall the information simply by mentally walking through the palace and describing the extraordinary figures contained therein (Cicero, 1954; Yates, 1992). The effectiveness of this mnemonic method has been supported by recent empirical studies showing digit span could be substantially increased when the digits are referenced using spatial indices in LTM (Darling, Parker, Goodall, Havelka, & Allen, 2014). In contrast to this classical strategy of referencing to-be-memorised information in WM to memorised information in LTM, more recently, integration of information to-be-encoded in WM, like the size of an object in the display, with information in LTM, like the real world size of the same object, has been suggested to follow Bayesian probabilistic inferences (Brady & Oliva, 2008).

1.2.2 Impact of sleep on WM

Sleep plays an important role in consolidation of memories. However, there are different sleep phases, each associated with specific neurophysiological processes. Additionally, there are multiple types of memories with distinct neural substrates. Therefore, it not surprising that the effect of sleep on memory consolidation has proven to be quite complex. Sleep is known to improve declarative, procedural as well as emotional memories (Diekelmann & Born, 2010). These beneficial effects have been demonstrated following both an overnight sleep as well as short daytime naps (Mednick, Nakayama, & Stickgold, 2003). Shorter delays between training and sleep also seem to lead to greater consolidation (Gais, Lucas, & Born, 2006; Talamini, Nieuwenhuis, Takashima, & Jensen, 2008). Slow wave sleep (SWS), characterised by synchronised neural activity over large swaths of cortex, has a particularly relevant role in consolidation of episodic, declarative memories (Plihal & Born, 1997; Plihal & Born, 1999). On the other hand, desynchronisation during Rapid Eye Movement (REM) sleep is helpful for consolidation of non-declarative memories, which may depend on localized circuitry changes (Plihal & Born, 1997;Plihal & Born, 1999; Wagner, Gais, & Born, 2001). Animal studies have consistently shown that the neural firing patterns in Hippocampal ensembles associated with spatial learning are reactivated during SWS and REM sleep (Ji & Wilson, 2007; Wilson & McNaughton, 1994). Regional cerebral blood flow measurements using Positron Emission Tomography (PET) in humans have shown comparable results: Hippocampal areas activated during spatial learning are reactivated during SWS with the level of reactivation correlating with post-sleep improvement in performance (Fuentemilla et al., 2013; Peigneux et al., 2004). Recently, improved performance on a spatial variant of n-back task has been reported following a naturalistic sleep period. It has been suggested that these results reflect an improvement in WM capacity (Kuriyama, Mishima, Suzuki, Aritake, & Uchiyama, 2008). These findings raise some crucial questions: Is the post-sleep improvement observed in WM simply a consequence of procedural learning? Or is it possible that sleep may improve WM performance by consolidating task-relevant LTM, which can then be exploited through interactions with WM?

1.3 Neural substrates of WM

1.3.1 Widespread cortical networks support WM

The search for the neural substrate/s of WM has over time revealed the complex nature of WM and helped evolve better theoretical models to understand it. A defining property of any neural substrate involved in WM is the persistence of neural activity in the absence of an external stimulus. Prefrontal cortical neurons in non-human primates were the first to show persistent stimulus-related activity during the delay phase of a WM task suggesting its role in WM (Funahashi & Bruce, 1989; Fuster & Alexander, 1971; Kubota & Niki, 1971). Since then, functional neuroimaging studies in humans have shown WM task-related changes in neural activity in Frontal, Parietal, Temporal and Occipital areas suggesting their role in WM (Courtney, Ungerleider, Keil, & Haxby, 1997; McCarthy et al., 1994; Ungerleider, Courtney, & Haxby, 1998; Wager & Smith, 2003). An important feature of the persistent neural activity associated with WM tasks is its modulation by memory load. Contralateral delay activity (CDA), sustained negative activity over Parietal and Occipital electrodes contralateral to the memorised targets, has been shown to increase with memory load till WM capacity limits are reached (Vogel & Machizawa, 2004; Vogel et al., 2005). Similar memory load dependent increase in BOLD signals has been shown in Prefrontal and Parietal areas (Todd & Marois, 2004, 2005). Considering that successful performance of a WM task involves recruitment of different cognitive operations including storage, rehearsal, binding, manipulation, etc., it is not surprising that multiple neural areas are activated during these tasks. However, the specific role of different areas activated during WM remains unclear.

Recent multi-voxel pattern analysis (MVPA) of fMRI signals has shown that information regarding the memorised target can be decoded from the MVPA patterns in Visual area V1 even though there is no task-related elevated activity seen (Harrison & Tong, 2009; Serences et al., 2009). In contrast, though the delay-period activity was elevated in Prefrontal and Parietal areas, MVPA analysis from these areas did not reveal any memorised stimulus-specific information (Emrich, Riggall, LaRocque, & Postle, 2013; Riggall & Postle, 2012). These findings suggest that elevated or memory-load-dependent neural signals may not be a defining feature of neural areas serving WM. The pattern of activity and the neural area where activity is observed may be stimulus and task-specific. Indeed, MVPA studies have shown that delay-period neural signals from different cortical areas represent task and role-specific information like memorised colour or orientation in Visual area V1, memorised motion in extrastriate areas, memorised complex visuospatial patterns in Occipital and Parietal areas, and task rules and contingencies, reflecting a top-down control, in Prefrontal cortex (Christophel, Hebart, & Haynes, 2012; Emrich et al., 2013; Harrison & Tong, 2009; Lee, Kravitz, & Baker, 2013; Riggall & Postle, 2012; Serences et al., 2009).

1.3.2 Role of medial Temporal lobe in WM

Individuals with damage to the medial Temporal lobe (MTL), including the most famous patient in memory research - HM, have demonstrated not only the importance of MTL in memory but also the distinction between different types of memories (Milner, Corkin, & Teuber, 1968; Scoville & Milner, 1957). Detailed studies have shown the Hippocampus, Entorhinal, Perirhinal and Parahippocampal cortices as the crucial MTL structures involved in memory (Corkin et al., 1997; Mishkin, 1978; Squire & Zola-Morgan, 1991; Zola-Morgan, Squire, Amaralt, Le Clair, & Micheletti, 1986). These patients show marked anterograde amnesia for episodic memories, but largely intact procedural memories. Crucially, earlier studies showed that these patients were able to retain information like digits, tones and shapes over short periods of time, suggesting that damage to MTL structures may not affect WM. However, later studies have shown that patients with bilateral MTL lesions have difficulty remembering simple shapes, novel objects, faces, scenes and associations even over short delays, sometimes lasting no more than few seconds (Axmacher et al., 2007; Ezzyat & Olson, 2008; Finke et al., 2008; Hannula, Tranel, & Cohen, 2006; Hannula & Ranganath, 2008; Olson, Moore, Stark, & Chatterjee, 2006; Piekema, Kessels, Mars, Petersson, & Fernández, 2006; Ranganath & D'Esposito, 2001). In fact, MTL lesions may even impair perceptual discrimination of scenes, faces and objects suggesting that MTL may be involved in processing specific information online as well as offline (Lee et al., 2005; Romero & Moscovitch, 2012; Warren, Duff, Jensen, Tranel, & Cohen, 2012).

Impairments observed in patients with different MTL lesions and activation patterns observed in functional imaging studies carried out in healthy controls have suggested that different MTL structures carry out process-specific and/or stimulus-specific operations. For example, imaging studies have shown selective response in the Hippocampus evoked by changes in the object-context relationship, while Parahippocampal cortex demonstrates response evoked by novel scenes (Howard, Kumaran, Ólafsdóttir, & Spiers, 2011). Similarly patients with Hippocampal lesions, including autoimmune encephalitis, which is thought to predominantly affect the Hippocampus, show impaired performance on tasks which require feature binding or context-to-object binding

(Pertzov et al., 2013). Based on these findings, it has been argued that Hippocampus is crucial for binding object information processed by Entorhinal cortex with contextual information processed by Parahippocampal area (Yonelinas, 2013). This view has, however, been challenged by imaging studies showing activation of Parahippocampal area in tasks involving spatial perception and memory or the appreciation of objects associated with highly specific spatial and non-spatial context (Aminoff, Gronau, & Bar, 2007; Düzel et al., 2003). Moreover, lesions of the Parahippocampal and Perirhinal cortex, in contrast to Perirhinal cortex alone, have been shown to lead to delay-dependent spatial memory impairments (Ploner et al., 2000).

1.4 Rationale and layout of thesis

The main aim of this thesis was to understand the nature of representations in vWM using psychophysical experiments with a view to build a model of WM that explains the limitations of contemporary models, specifically the slots and resources models.

In Chapter 2, I will describe a series of psychophysical experiments that provide evidence to show that high-resolution spatial information in vWM is stored in local maps while as configurational information is stored in coarse representations.

In Chapter 3, I will present another set of psychophysical experiments to show the nature of interaction between WM and LTM and the impact of sleep on WM. Specifically, I will provide evidence to show that LTM does not improve fine detailed encoding of spatial information in WM but facilitates recall through well-learnt landmarks. Additionally, I will provide data to show that sleep immediately after the learning phase consolidates the effect of learnt landmarks on WM, though has no overall impact on WM capacity.

In Chapter 4, I will present a series of psychophysical and behavioural experiments comparing data from a patient with bilateral medial Occipito-Temporal cortical (mOTC) lesions but spared Hippocampi and Entorhinal cortices with matched healthy controls. The data will provide evidence to show that bilateral mOTC damage impairs binding of spatial and non-spatial information in WM and leads to disproportionate temporal decay of WM representations.

In Chapter 5 I will provide a summary and general discussion of the findings.

Chapter 2: Fine-grained, local maps and coarse, global representations support human spatial working memory

2.1 Abstract

While sensory processes are tuned to particular features, such as an object's specific location, colour or orientation, visual working memory (vWM) is assumed to store information using representations, which generalise over a feature dimension. Additionally, current vWM models presume that different features or objects are stored independently. On the other hand, configurational effects, when observed, are supposed to mainly reflect encoding strategies. We show that the location of the target, relative to the display centre and boundaries, and overall memory load influenced recall precision, indicating that, like sensory processes, capacity limited vWM resources are spatially tuned. When recalling one of three memory items the target distance from the display centre was overestimated, similar to the error when only one item was memorised, but its distance from the memory items' average position was underestimated, showing that not only individual memory items' position, but also the global configuration of the memory array may be stored. Finally, presenting the non-target items at recall, consequently providing landmarks and configurational information, improved precision and accuracy of target recall. Similarly, when the non-target items were translated at recall, relative to their position in the initial display, a parallel displacement of the recalled target was observed. These findings suggest that fine-grained spatial information in vWM is represented in local maps whose resolution varies with distance from landmarks, such as the display centre, while coarse representations are used to store the memory array configuration. Both these representations are updated at the time of recall.

2.2 Introduction

Early students of cognition viewed the relation between memory and perception as analogous to that between a portrait and the scene portrayed (Aristotle, 1984; Yates, 1992). Moreover, a long-standing intellectual tradition has since held that all memories are, or can be, spatially organized, since imposing a spatial structure facilitates the maintenance and recall of information, whether visual or conceptual (Cicero, 1954; Yates, 1992). While a prominent contemporary account of working memory (WM) has embraced this original metaphor of visual memory as a sketch of previously viewed scenes (Baddeley, 2003; Baddeley & Hitch, 1974), recent investigations examining the limits to the information that can be held in visual working memory (vWM), do not support a spatially based, analogical model of vWM (Bays & Husain, 2008; Luck & Vogel, 1997). Initially, the observations that the ability to detect changes between subsequently presented scenes degraded rapidly when the scenes contained more than three or four objects, regardless of their complexity, led to the suggestion that visual data are stored in a limited number of object specific slots, each slot endowed with unlimited resolution (Luck & Vogel, 1997). Later, this model was revised to account for the fact that recall of visual data shows decrements whenever more than one object is held in vWM. The revised model suggested instead that slots have limited resolution and when the number of objects held in memory is less than the number of slots, more than one slot is used to store the same object (Zhang & Luck, 2008). Improved recall precision can then be achieved by averaging over independent memory representations. An alternative interpretation of the gradual decline in recall precision with memory load is that limited resolution resources are used to represent specific visual dimensions, such as colour, position and orientation (Bays & Husain, 2008; Bays, Wu, & Husain, 2011). Consequently, as the number of features in a given dimension increases, a smaller fraction of the global resource is available to represent each feature. This model predicts no upper limit on the number of features, and consequently objects, that can be held in memory, but shares with the former model the assumption that memory resources are not tuned to specific features within a given dimension. These proposals imply that memory differs from sensory representations in Visual cortex, which are tuned to specific features, such as the specific location, orientation or colour (Hubel & Wiesel, 1974; Smith et al., 2001).

A large body of neurophysiological work has indicated that during maintenance of information in vWM, sustained increases in neural activity take place in Frontal and Parietal areas, which are modulated by memory load (Todd & Marois, 2005; Vogel & Machizawa, 2004). The early slot model provided an elegant explanation of these findings, since the amplitude of the sustained neural activity appeared to track the number of slots utilised. However, neither the revised version of the slot model nor the resource model account for the effects of memory load on the amplitude of delay period neural activity, since both assume that memory utilises all available slots or resources, irrespective of memory load. Interestingly, more recent fMRI data suggest that visual information can be decoded from spatial patterns of BOLD activity in early Visual cortical areas, during the delay phase of vWM tasks, even though no overall increase in BOLD activity is observed there (Lee et al., 2013; Serences et al., 2009). Considering that these cortical regions contain neurons with receptive fields that span limited areas of the visual field, the aforementioned fMRI findings suggest that capacity limitations in recalling the details of a memorised scene depend on spatially curtailed processes and hence that a target's position may affect the resolution of its memory representation.

Moreover, neither slots nor resource models, which assume that features belonging to different objects are stored independently of each other, account for the finding that recall of a specific feature not only depends on the value of that feature, but also on the values of other features of the same dimension within the memory array (Hu & Goodale, 2000; Huang & Sekuler, 2010). Further evidence for global effects in vWM is provided by the finding that neural responses in Parietal regions of non-human primates, performing a match to sample task, are affected by the spatial configuration of the memory array, but are invariant to the position of the array in the visual field (Chafee, Averbeck, & Crowe, 2007; Chafee, Crowe, Averbeck, & Georgopoulos, 2005), suggesting that higher order neurons update their spatial selectivity, to gain access to the configuration of the visual scene.

We examined how precision and accuracy of spatial recall depends on local factors, namely the location of the memory target, global factors, namely the overall configuration of the items held in memory and configurational information presented at recall. We found that recall precision depends not only on the number of items held in memory, as previously reported (Bays & Husain, 2008; Luck & Vogel, 1997), but also on the target location, while recall accuracy depends on the overall spatial configuration of the memorised items. Moreover, presenting configurational information at recall affected both the accuracy and precision of recall. We propose that spatial information is maintained in both local, variable resolution spatial maps, and coarse representations of the overall configuration of the memory items and that both representations are updated at the time of recall.

2.3 Methods

2.3.1 Participants

All experimental protocols were approved by the Research Ethics Committee at Bangor University. Participants gave written informed consent prior to commencing experimental procedures and were remunerated for their participation. All participants were adults with no known neurological disorder and were not taking psychotropic medications at the time of testing (Appendix 1). Participants had normal or corrected-to-normal visual acuity and colour vision.

2.3.2 Stimuli and experimental procedures

2.3.2.1 Experiment 1

Eight participants (three females) with a mean age of 29.5 years (s.d.= 7.3 years) took part in the colour-cue experiment. The experiment was controlled by a custom coded script in Matlab© running on an Apple iMac 10. The visual display was controlled using a set of freely available procedures (Brainard, 1997; Kleiner & Brainard, 2007). The display was an LCD monitor (NEC LCD3210). The monitor subtended 25.84^0 x 25.84^0 of visual angle. Participants' head position was restrained by a chin rest, which ensured that a constant distance of 85.0cm from the display was kept during the experiment.

Participants were instructed to fixate a central cross at the beginning of each trial and during the inter-trial interval, but were encouraged to move their eyes to examine the items of the sample array and the recall display. Participants completed initially a practice block of fifty trials to gain familiarity with the task. Each participant was subsequently tested over separate sessions, run over four consecutive days. Each session consisted of four hundred and fifty trials divided into three blocks of one hundred and fifty trials each. The memory load varied over two levels: participants remembered the location of either one or three discs. The order of trials containing either one or three memory items was randomized within blocks.

The sample display contained either one or three red, green, or blue discs displayed on a grey background. The discs occupied nine possible positions, including the centre of the display and the corners of two concentric, imaginary squares tilted 45^0 relative to each other. The items' locations were jittered on each trial, by adding independent, identically distributed two-dimensional Gaussian noise (σ=0.7°). The recall at each target location was probed in eighty-eight trials, when the display contained a single memory item, and in one hundred and twelve trials, when it contained three memory items. The set of display configurations containing three memory items was obtained by exhaustive combination of nine target locations and fifty-six permutations of the two non-target items.

Each trial started with a 1.0s long presentation of a fixation cross at the centre of the display. This was followed by sample array containing either one (displayed for 1.5s) or three discs (displayed for 2.4s), which allowed adequate time for an exhaustive inspection of each item. This was followed by a 0.2s pattern mask containing a pseudorandom luminance pattern of bright and dark pixels. A 1.3s long blank screen immediately followed. The target, whose location the participants were asked to replicate, was probed by an electronically recorded voice, which indicated its colour. The participants reported the target location by moving a cross-hair cursor to the memorised location via a hand held mouse (Fig. 2.1A). Participants were instructed to be as accurate as possible, without any time limitations. To ensure that participants memorised the colour also when a single disc was presented, in 10% of these trials, the instructed and the target colour differed; participants were asked to place the cursor at the edge of the display in trials in which target and probed colour differed.

2.3.2.2 Experiment 2

Four participants (one female), with a mean age of 34.2 years (s.d. = 8.4 years), were tested in the recall probe translation/rotation experiment. The stimuli, apparatus and procedures were identical to those used in location probe experiment, except that it only included trials containing three memory items. Moreover, in the recall display, the position of the two memory items was either translated, down and to the left or up and to the right, or rotated clockwise or anticlockwise (Fig. 2.3A). The displacement was 0.6^0 of visual angle for translation and 5^0 around the line of sight for rotations - resulting in mean displacement of memory items in the image plane of 0.6^0. Participants were not told that the location of the non-target memory items could change at recall. These trials were mixed within blocks of experiment 3. There were eight hundred and fifty-eight trials each for translation and rotation conditions. For each participant, all possible combinations of target and non-target locations were tested an equal number of times – each location being tested sixty-six times for both the translation and rotation conditions.

2.3.2.3 Experiment 3

Four participants (one female) with a mean age of 34.2 years (s.d. = 8.4 years) were recruited. Procedures were identical to those used in experiment 1, except for the outline of the display, the location of the stimuli and the report procedure. The stimuli were presented on the LCD screen using its native rectangular aspect ratio. The screen subtended 44.8^0 x 25.8^0 of visual angle and was placed at a distance of 85.0cm from the participant. Visual stimuli appeared at one of thirteen possible locations, which included the centre of the display and the corners of two concentric hexagons tilted 90^0 relative to each other. The memory items were bright discs displayed on a grey background. The items' locations were jittered by 2D, independent identically distributed Gaussian noise (σ=0.7°).

When three memory items were presented in the sample display, two of the memory items were shown again in the recall display. The participants were instructed to report the location of the remaining target. When the sample display contained a single memory item, the recall display included only the cursor cross-hair, which was used to indicate the target location (Fig. 2.4A). Each participant was tested in fourteen, consecutive, daily sessions. In each session, participants completed five hundred and seven trials over three blocks comprising hundred and twenty-seven trials each and one comprising hundred and twenty-six trials. For each participant, all possible combinations of target and non-target locations were tested an equal number of times - each location being tested eighty-four times for the one memory item condition and four hundred and sixty-two times for the three memory items' condition.

2.3.2.4 Experiment 4

Six participants (five females) with a mean age of 20.3 years (s.d. = 1.6 years) took part in this experiment comparing the effects of location and colour probes on recall. The stimuli, apparatus and procedures were identical to those used in the previous experiments, except for the memory locations, the recall procedure, and the fact that sample display always contained three stimuli. The stimuli appeared at twelve possible locations as described in experiment 3, except for the centre one. In half the trials, the recall probe was the colour of the target, in the other half, the locations of the non-target items (Fig. 2.5A). The colour and location probes were used in separate blocks. Each participant was tested over four, consecutive daily sessions. Each session consisted of three alternating colour and location probes blocks, whose order was counterbalanced across participants. Each block contained hundred and forty-three trials each. All possible combinations of target and non-target locations were tested an equal number of times - each location being tested sixty-six times in both probe conditions.

2.3.2.5 Experiment 5

Ten participants (six females), with a mean age of 29.1 years (s.d. = 6.19 years), were recruited to examine the effects of mixing the two probe conditions within blocks. The stimuli, apparatus and procedures were similar to those used in experiment 4, except for the location of memory items, and the use of both colour and location probes within the same block. The stimuli appeared at thirteen possible locations, including the centre of the display and the corners of three concentric squares tilted 45^0 relative to each other. The colour and location probe trials were randomly intermixed, ensuring that participants memorised both the colour and location of the stimuli in each trial. Each participant was tested over four daily sessions, each session consisting of three blocks of hundred and forty-three trials. All possible combinations of target and non-target locations were tested an equal number of times - each location being tested sixty-six times for both probe conditions.

2.3.3 Data analysis

The aim of the analysis was to quantify the systematic and variable components of the errors made when recalling the target location. The systematic recall error was the difference between recalled and actual target location, which was consistently repeated over trials. Operationally, it was defined as the average difference between recalled and actual target location, as estimated by linear regression models (see below). The variable error was the error component, which varied from trial to trial. It was defined as the root square of the mean squared difference between recalled and actual target location, after removing any systematic difference. The reciprocal values of these two error components are referred to as accuracy and precision, respectively. The following paragraphs detail the specific procedures we used to estimate the systematic and variable errors.

2.3.3.1 Systematic error (recall accuracy)

The systematic error was assessed both over all target locations simultaneously, as well as separately for each canonical target location. The aim was to examine the systematic errors as a function of the memory load, and the effect of memory items' spatial configuration on the recalled target location. Prior to the analysis, trials were removed in which the reported location was closer to a non-target memory item than the target. These trials never amounted to more than 2% of the trials in all of the participants and experiments.

The following linear model was used to estimate the relation between target location and recalled location:

$$\begin{bmatrix}\theta_r\\ \phi_r\end{bmatrix}=\begin{bmatrix}a_0\\ b_0\end{bmatrix}+\begin{bmatrix}a_1\,a_2\\ b_1\,b_2\end{bmatrix}\begin{bmatrix}\theta_t\\ \phi_t\end{bmatrix}+\begin{bmatrix}\varepsilon_\theta\\ \varepsilon_\phi\end{bmatrix}$$

where θ_r and ϕ_r are the reported azimuth and elevation, θ_t and ϕ_t the target's azimuth and elevation, while ε_θ and ε_ϕ are the variable errors, assumed to be drawn from zero mean, normal distributions with degrees of freedom equal to the number of trials minus three. The parameters of the model were estimated using a least square procedure. The above model was applied to data obtained at each target location, using only trials in which the target appeared, after its location had been jittered, within 2.5° of its canonical location. The recalled locations, for each canonical target position, were estimated by substituting the coordinates of the canonical target location in the model above.

To further examine the global effects of memory load on target recall, the model was used to analyse data, which included trials from all target locations, separately for each level of the memory load. The estimated parameters were transformed into tensors of the systematic error field. This set included the divergence, curl and two shear components of the systematic error vector field. These tensors captured respectively the tendency to overestimate or underestimate 1) the target distance from the display centre, 2) the orientation of the target relative to the centre of the display, 3) the target distance from the display centre unequally along the horizontal and vertical axes, and 4) the target distance from the display centre unequally along the two main oblique axes of the display (Fig. 2.2c). The tensors were computed using the following formulas:

Divergence = $(a_1 - 1) + (b_2 - 1)$

Curl = $a_2 + b_1$

Shear₁ = $(a_1 - 1) - (b_2 - 1)$

Shear₂ = $a_2 - b_1$

When three items were memorised, the systematic error was also estimated using a linear model, whose regressors included the target location in screen coordinates as well as in centre of the memory items' configuration (CM) coordinates. The CM coordinates of the target ($\theta_t^{cm}, \phi_t^{cm}$) were computed from its (θ_t^s, ϕ_t^s) and the non-target memory items screen coordinates, using the following expression:

$$\theta_t^{cm} = \theta_t^s - \sum_{i=1}^{n} \frac{\theta_t^s}{n}$$

$$\phi_t^{cm} = \phi_t^s - \sum_{i=1}^{n} \frac{\phi_t^s}{n}$$

where n is the number of memory items. The linear model thus contained four regressors, in addition to the constant terms:

$$\begin{bmatrix}\theta_r\\ \phi_r\end{bmatrix}=\begin{bmatrix}a_0\\ b_0\end{bmatrix}+\begin{bmatrix}a_1 & 0 & a_3 & 0\\ 0 & b_2 & 0 & b_4\end{bmatrix}\begin{bmatrix}\theta_t\\ \phi_t\\ \theta_t^{cm}\\ \phi_t^{cm}\end{bmatrix}$$

The parameters which modelled the crossed effects of the target azimuth and elevation, in screen and CM coordinates, on the recalled target elevation and azimuth respectively, were set to zero, since a preliminary analysis indicated that their group level contribution to the linear fits was neglicable.

2.3.3.2 Effects on target recall of translating and rotating the position of non-target items

In experiment 2 we either translated or rotated the position of the non-target items at recall. The effect of these positional changes on target recall was estimates using a linear regression procedure.

Translation of the non-target items took place always along the main oblique axis, either down and to the left or up and to the right. Therefore the displacement of the non-target items along azimuth and elevation had the same magnitude T. The effect on the recall of the target azimuth and elevation could then be estimated using the following model:

$$\begin{bmatrix}\theta_r\\ \phi_r\end{bmatrix}=\begin{bmatrix}a_0\\ b_0\end{bmatrix}+\begin{bmatrix}a_1 & a_2 & a_3\\ b_1 & b_2 & b_3\end{bmatrix}\begin{bmatrix}\theta_t\\ \phi_t\\ T\end{bmatrix}$$

The horizontal and vertical components of the red line shown in Fig. 2.3B are the group averaged values of a_3 and b_3 respectively.

Rotation of the non-target items position took place around an orthogonal axis through the screen centre. We estimated the effects of rotation on target recall along the direction, which would have resulted in a rigid rotation of the target and non-target memory items. The target displacement, which would have resulted in a rigid rotation of the array, was computed on each trial using the following equation:

$$\begin{bmatrix} R_x \\ R_y \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \theta_t \\ \phi_t \end{bmatrix}$$

where α is the angle of rotation around the orthogonal axis and R_x and R_y are the displacements of the target azimuth and elevation, respectively, required to maintain the rigid configuration of the memory array. The effect of non-target items rotation on target recall was then computed using the following model.

$$\begin{bmatrix} \theta_r \\ \phi_r \end{bmatrix} = \begin{bmatrix} a_0 \\ b_0 \end{bmatrix} + \begin{bmatrix} a_1 & a_2 & a_3 & 0 \\ b_1 & b_2 & 0 & b_4 \end{bmatrix} \begin{bmatrix} \theta_t \\ \phi_t \\ R_x \\ R_y \end{bmatrix}$$

The horizontal and vertical components of the red line shown in Fig. 2.3C are the group averaged values of a_3 and b_4 respectively.

2.3.3.3 Recall variable error (recall precision)

The azimuthal and elevational components of the variable error were estimated at each target location. For each target location, the systematic recall error was computed using a separate linear model, as described above. The residuals $\varepsilon_{1,\ldots\ldots,n}$ of the linear model, over n trials, were rank ordered and their cumulative probability score p_r was computed from their rank, r, as follows:

$$p_r = \frac{r}{n+1}$$

The cumulative probabilities were transformed into z scores using the probit function:

$$probit(p_r) = \sqrt{2} \cdot erf^{-1}(2p_r - 1)$$

The computation of the linear model and the residuals was then repeated, the second time after trials, whose z scores lay outside the interval (-1.8, 1.8), had been excluded. However, the z scores were not recomputed.

The standard deviation of the error was estimated by fitting the following model:

$$\varepsilon = c_0 + c_1 z$$

where ε is the set of variable errors and c_1 the estimated standard deviation σ of the variable errors, that is:

$$\overline{\sigma} = c_1$$

This procedure provides an estimate of the error standard deviation that is robust in the face of outliers due, for example, to accidental mouse clicks or guesses.

2.3.3.4 Assessing the effects of memory load on variable error

A central issue in this work is the nature of the relation between the effects of target location and memory load on recall variable error. First, we examined whether target location and memory load exert independent, additive effects on the recall error variance, as one would predict if the effects of target location and those of memory load arise at different processing stages. If target location and memory load exert independent effects then the recall error variance should simply be the sum of the variances due to each, and show no interaction between these two factors.

Having found that the target location and memory load interact (see Results), we then examined the nature of this interaction. We assumed that the recall error at each location varied multiplicatively with the memory load. In other words, the ratio between the variances of the recall error, when the memory load was three and one respectively, was constant across target locations:

$$\sigma(\theta,\phi)^2_{load=3} = a \cdot \sigma(\theta,\phi)^2_{load=1}$$

We compared this multiplicative model to a model, which assumed that the variance of the recall error when the memory load is three, is the sum of two components: 1) the error made when the memory load is one, whose variance varies with target location, and 2) an error of constant variance, which does not change with target location:

$$\sigma(\theta,\phi)^2_{load=3} = c + \sigma(\theta,\phi)^2_{load=1}$$

The parameters of the two models, namely a and c, were estimated separately for each observer using a maximum likelihood procedure. The log-likelihood, Λ, for the multiplicative model was computed by integrating the product of two posterior chi-squared distributions of the measured error variances, at each target location, and by summing their logarithms over locations:

$$\Lambda(a) = \sum_{i=2}^{9} \log_2 \left[\int_{0.2\cdot\min(\sigma^2_{load=1})}^{10\cdot\max(\sigma^2_{load=1})} \chi^2_{df_{load=1,i}}\left(\frac{\sigma^2_{load=1,i}}{\nu}\right) \cdot \chi^2_{df_{load=3,i}}\left(\frac{\sigma^2_{load=3,i}}{a\nu}\right) \partial \nu \right]$$

The log-likelihood for the additive model was computed similarly:

$$\Lambda(c) = \sum_{i=1}^{9} \log_2 \left[\int_{0.2\cdot\min(\sigma^2_{load=1})}^{10\cdot\max(\sigma^2_{load=1})} \chi^2_{df_{load=1,i}} \left(\frac{\sigma^2_{load=1,i}}{\nu} \right) \cdot \chi^2_{df_{load=3,i}} \left(\frac{\sigma^2_{load=3,i}}{c+\nu} \right) \partial \nu \right]$$

The limits of integration were set between two values corresponding to a fifth of the smallest and ten times the largest variance, when the memory load was one. A simplex algorithm was used to search for the values of the parameters a and c, which maximized the respective likelihood functions. The two maximum log-likelihoods were then compared to establish which of the two models provided a better fit to the data.

2.4 Results

2.4.1 Target location and memory load affect spatial recall precision

To characterise spatial recall performance, the systematic and variable components of the recall errors were quantified separately. The systematic error is the component that is consistently repeated over trials, while the variable error is the component whose value changes unpredictably trial by trial. The terms recall 'accuracy' and 'precision' are used throughout this paper to refer to the reciprocal of the magnitude of the systematic and variable errors, respectively.

We measured the precision in recalling the position of simple coloured discs, when one or three were presented in the sample display (Fig. 2.1a). Figs. 2.1b and c show that the target location affected the standard deviation of the variable error of spatial recall. Specifically, targets located between the centre and the boundaries of the display, were recalled less precisely than targets close to either the centre or the boundaries of the display, suggesting that proximity to stable landmarks may facilitate the encoding and recall of spatial data in vWM. Moreover, the effect of target location on spatial recall was qualitatively similar whether the participants memorised one or three items. However, memory load did change the overall recall precision, which was diminished when the participants had to remember three rather than one item. Two-way, repeated-measures ANOVAs confirmed that the variance of the recall error was affected by the target position along horizontal axis' target horizontal position, namely target azimuth - $F(8,56) = 16.46$, $p < 0.001$; the target position along vertical axis, namely target elevation - $F(8,56) = 29.18$, $p < 0.001$), and memory load (for target azimuth - $F(1,7) = 30.61$, $p = 0.001$; for target elevation - $F(1,7) = 25.44$, $p = 0.001$). Interestingly, there was a significant interaction between target location and memory load (azimuth - $F(8,56) = 8.29$, $p < 0.001$; elevation - $F(8,56) = 8.33$, $p < 0.001$), strongly suggesting that the effects of

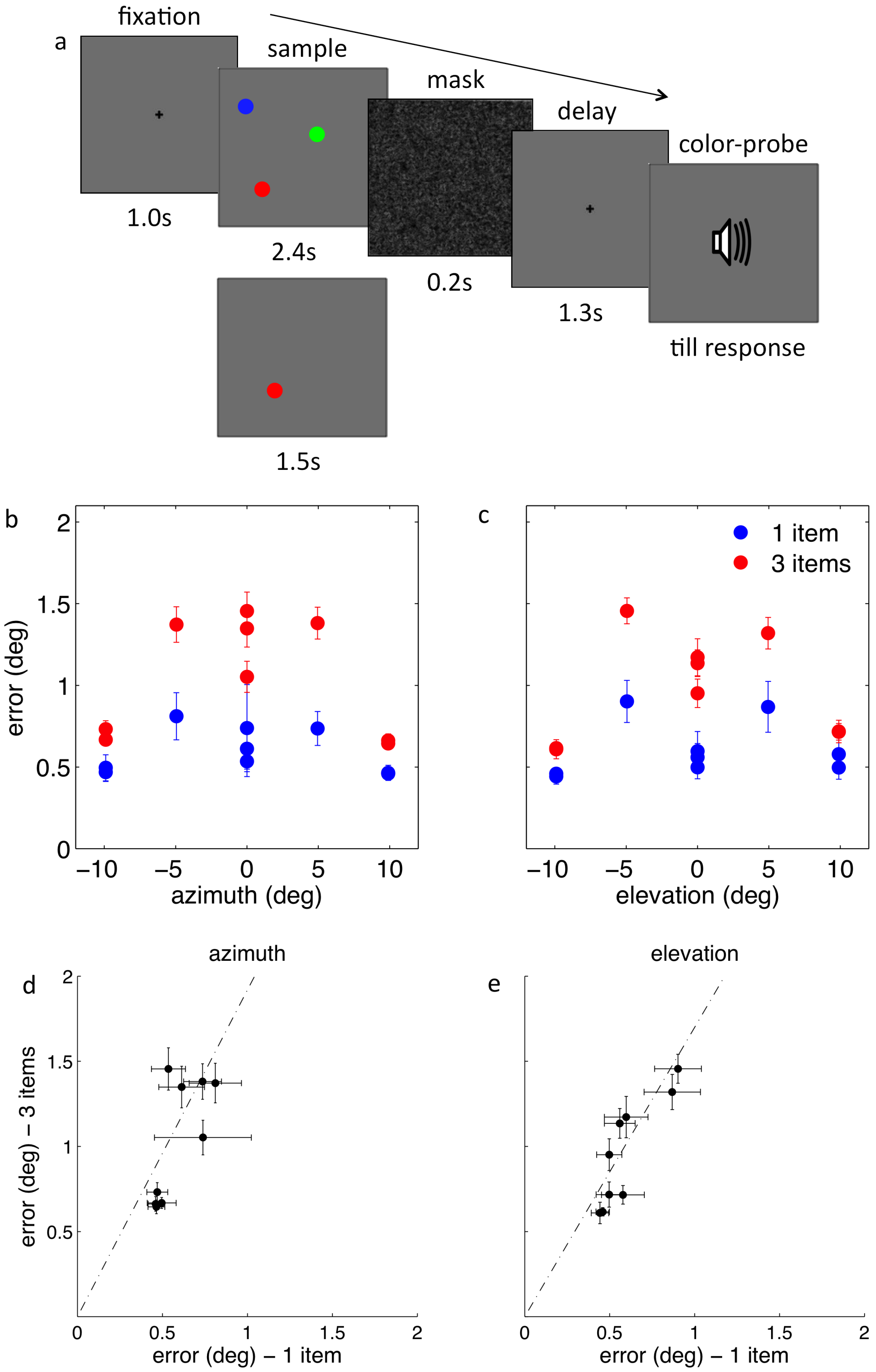

Figure 2.1: *Memory load and target location affect spatial recall. a) Participants memorised the location of either one or three items. After a pattern mask and blank interval, the target to be recalled was indicated by its colour. b) The standard deviation of the recall error is shown as a*

function of target azimuth, when the memory load is one (in blue) and three (in red). c) The recall error as a function of target elevation. The variable error is smaller for targets closer to the centre and boundaries of the display compared to intermediate positions. d) The standard deviation of the recall error when memory load was three is shown as a function of the error standard deviation when memory load was one for target azimuth, and e) elevation. Each point represents the group averaged error standard deviation at one of the nine target locations. The vertical and horizontal error bars are standard errors of the mean. The dash-dot line represents the group average best fitting multiplicative model.

target location and memory load on recall precision are not independent. This result is important since it is at odds with the possibility that the effects of target location and memory load on recall arise at separate stages. For example, a plausible hypothesis could have been that memory load effects reflect the limited capacity of WM, while those of target location, the spatiotopic organization of early perceptual mechanisms. However, if this were the case, the effects on recall variance of target location would be additive with those of memory load, which is contrary to the finding reported above. Figs. 2.1d and e show, for each target location, the group averaged recall error's standard deviation, when memory load was three, as a function of the standard deviation of the error, when memory load was one. The relation between the standard deviations is multiplicative rather than additive. We estimated, participant by participant, the best fitting additive and multiplicative models. The log-likelihood of the multiplicative model was greater than the log-likelihood of the additive model in all participants (azimuth - $t(7) = 3.11$, $p = 0.017$; elevation - $t(7) = 3.10$, $p = 0.017$), except one, in whom the effects of memory load were least prominent. Moreover, we found that the error standard deviation at each of the target locations was proportional to the square root of the memory load. In fact, the recall error standard deviation, when observers memorised three items, was 1.87 (95% CI = 1.74-2.00) and 1.70 (95%CI = 1.64-1.76) times greater than when observers memorised only one item, for target azimuth and elevation, respectively. These values are consistent with previous estimates of the effect of memory load on recall error (Bays & Husain, 2008). These findings suggest that spatial WM depends on spatially curtailed representations, whose resolution scales with the overall memory load and the target location.

2.4.2 Memory load modulates systematic errors

It is known that recall of spatial information from WM shows systematic distortions, which depend on both stimulus and task related factors (Diedrichsen, Werner, Schmidt, & Trommershäuser, 2004; Nelson & Chaiklin, 1980). Some have also suggested that these biases reflect the reference frames used to encode spatial data in memory (Sheth & Shimojo, 2001). We characterised the spatial structure of systematic recall errors, separately for the two levels of memory load employed. Two patterns of systematic recall errors were found. Fig. 2.2a shows that when the memory load was one, participants overestimated the target's distance from the display centre, more prominently so along azimuth than elevation. Moreover, observers recalled the target at a lower elevation than its location in the sample display warranted. However, when memory load was three, participants tended to underestimate the target's distance from the centre of the screen (Fig. 2.2b). Two-way, repeated-measures ANOVAs showed a significant interaction of target location by memory load (azimuthal - $F(8,56) = 3.11$, $p = 0.006$; elevational - $F(8,56) = 3.09$, $p = 0.006$) on the systematic error, thus confirming that the systematic recall error was modulated by memory load.

To characterise the spatial structure of recall inaccuracies and gain further insight into the nature of the load effects, we reparametrized the systematic recall error using a set of four tensors, namely the divergence, rotation and two shear components of the vector error field (Fig. 2.2c). Paired-samples t-tests indicated that of the four tensors, only the divergence of the error field ($t(7) = 3.36$, $p = 0.012$; Fig. 2.2d) showed a significant effect of memory load,

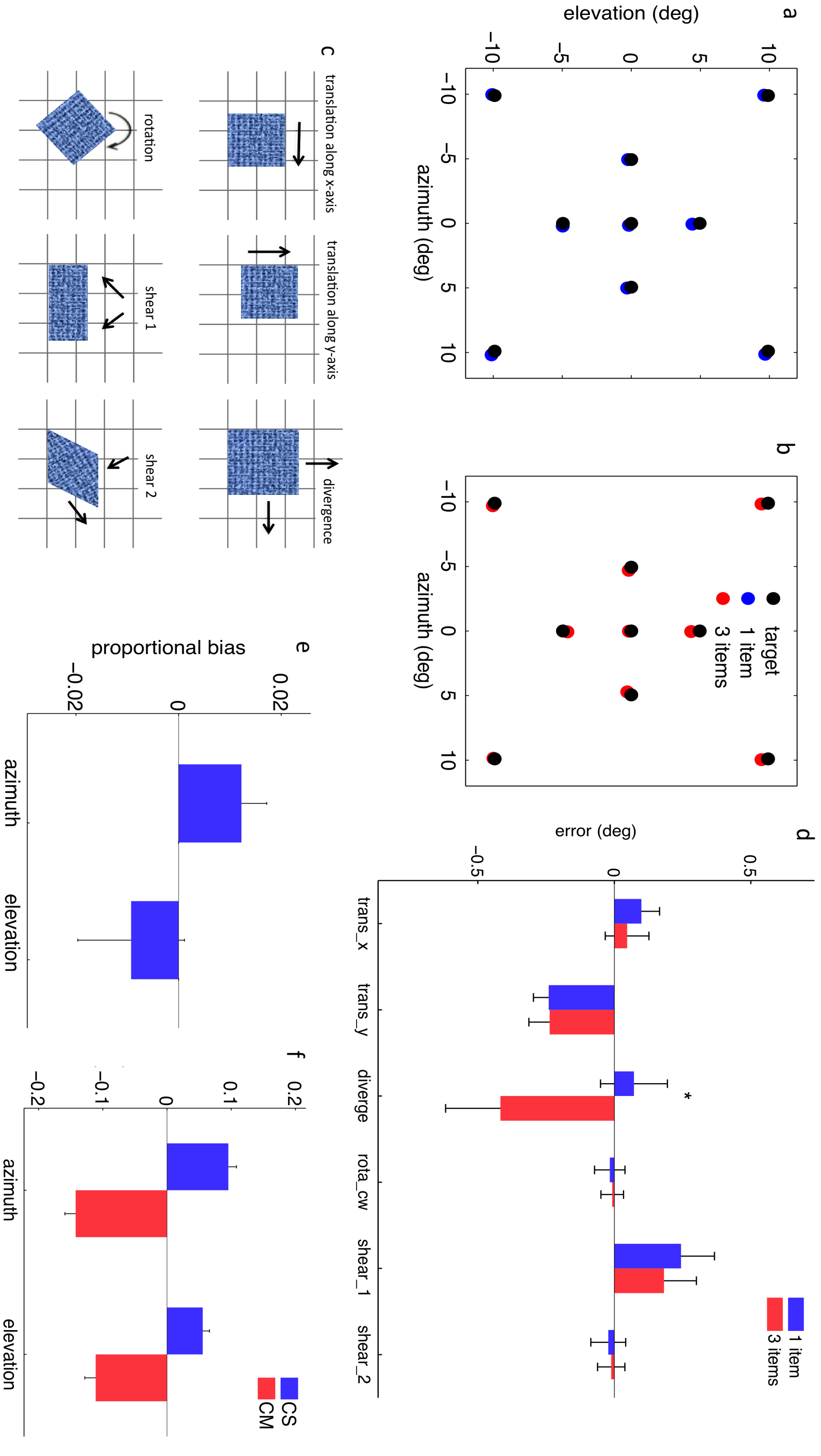
a
elevation (deg)
10
5
0
−5
−10
azimuth (deg)
−10
−5
0
5
10
b
● target
● 1 item
● 3 items
azimuth (deg)
−10
−5
0
5
10
c
translation along x-axis
translation along y-axis
divergence
rotation
shear 1
shear 2
d
error (deg)
0.5
0
−0.5
1 item
3 items
*
trans_x
trans_y
diverge
rota_cw
shear_1
shear_2
e
proportional bias
0.02
0
−0.02
azimuth
elevation
f
0.2
0.1
0
−0.1
−0.2
CS
CM
azimuth
elevation

Figure 2.2: *Memory load affects systematic recall error. a) Recalled targets were systematically displaced outward and downward (in blue) relative to their location in the sample display (in black) when the memory load was one. b) Recalled targets were displaced toward the centre of the display when the memory load was three (in red). c) The six spatial components of the systematic error are shown, including constant offsets (translation) along azimuth and elevation, and four linear tensors. d) Memory load only affected the divergence of the error field. For the sake of convenience, the error size is expressed in degrees for the tensors as well. These values correspond to the displacement associated with each component, averaged over all target locations. e) Proportional recall bias in centre of screen (CS) coordinates (in blue) when the memory load is one. f) Proportional recall bias in CS (in blue) and centre of the memory items' configuration (CM) coordinates (in red) when the memory load is three. Target azimuth, in CS coordinates, was overestimated both when the memory load was one and three. In addition, when the memory load was three, participants underestimated both target azimuth and elevation in CM coordinates. trans - translation, diverge - divergence, rota_cw - clockwise rotation.* *$p < 0.05$.

suggesting that the effects of memory load can be characterised using a single spatial component, namely the tendency to either under or overestimate the target distance from the display centre.

2.4.3 Spatial memory representations are based on multiple reference frames

Next, we investigated why memory load affects spatial distortions in recall. We observed that when participants had to keep three items in memory, the reported target location was shifted toward the locations occupied by the other two memory items, suggesting that spatial distortions, when the memory load increases, arise in a reference frame centred on the memory items. Spatial distortions were thus modelled using two sets of linear regressors. The first set consisted of the target location in screen coordinates (CS), the second of the target location in the centre of the memory items' configuration coordinates (CM). The target azimuth in CS coordinates was overestimated, when the memory load was both one (azimuth - $t(7) = 2.48$, $p = 0.042$; for elevation - $t(7) = -0.89$, $p = 0.40$) and three (azimuth - $t(7) = 7.50$, $p < 0.001$; elevation - $t(7) = 5.27$, $p = 0.001$), however the target location in CM coordinates was underestimated (azimuth - $t(7) = -8.48$, $p < 0.001$; elevation - $t(7) = -6.59$, $p < 0.001$), when memory load was three (Figs. 2.2e,f), suggesting that the change in the direction of the systematic error with memory load reflects the additive effects of two spatial representations, arising in two different reference frames.

The spatial configuration effects we observed may arise either because spatial data are smeared by vWM or because participants hedge their bets at recall, reporting an intermediate location, when they are not fully confident about which of the memory items is the recall target, and not because the location of the items held in memory is encoded in a reference frame centred on CM. To examine this possibility, in experiment 2, the target was identified by presenting the non-target memory items at recall, but the non-target items were either translated away from the position they had occupied in the sample display 0.6^0 up and to the right or 0.6^0 down and to the left (Fig. 2.3a), or rotated around an orthogonal axis passing through the display centre, which resulted in a mean displacement of the memory items of 0.6^0 (also Fig. 2.3a). These trials were randomly intermixed within blocks in which the remaining 80% of the trials were from experiment 3. As shown in Fig. 2.3b, the recalled target location was shifted on average by 0.4^0 in the same direction along which the memory items had been translated (azimuth - $t(3) = 10.06$, $p = 0.002$; elevation - $t(3) = 6.10$, $p = 0.009$), suggesting that participants memorised and reported the target location relative to the other two items' position. One possibility is that translating the non-target items shifts the origin of the reference frame, namely the CM, used to recall the target location. The other is that participants may have reported the target location, which preserves the distance of the target

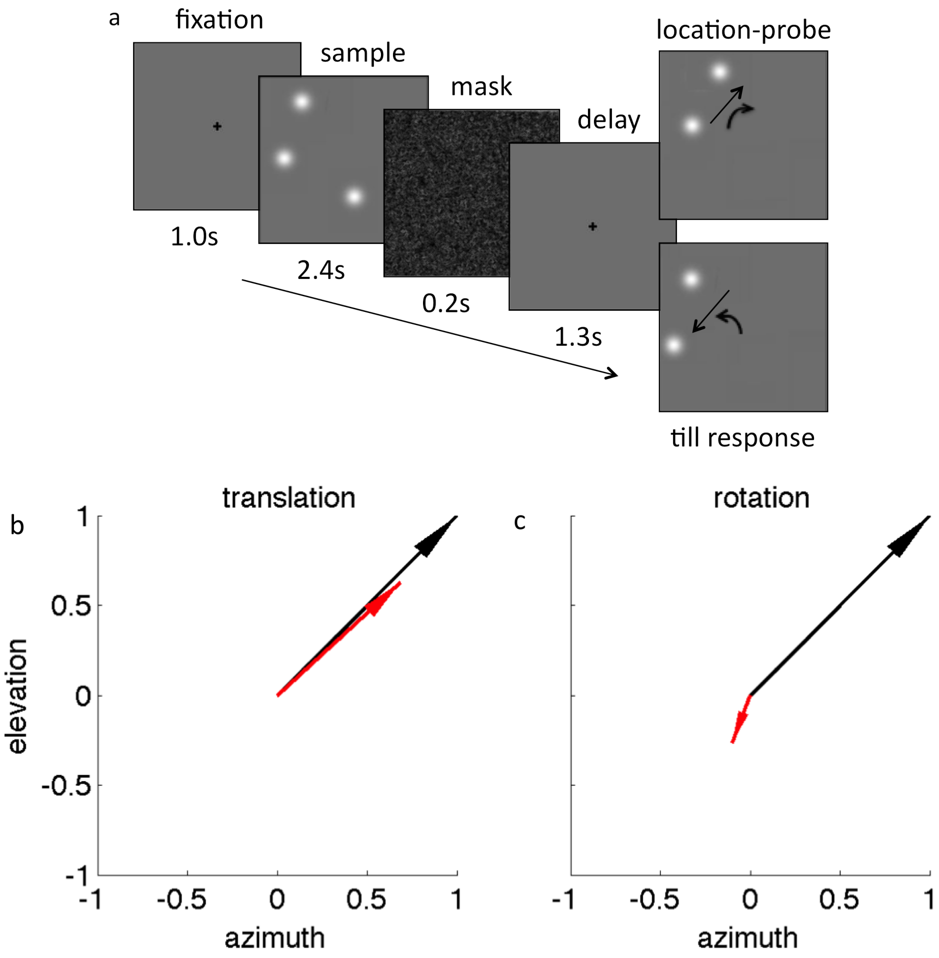

Figure 2.3: *Location-probe displacement affects target recall. a) The target was identified by displaying the position of the non-target memory items at recall. The position of the non-target items was either translated obliquely (straight arrows) or rotated around an axis through the display centre (curved arrows). b) Translation of the non-target items, whose direction and magnitude is portrayed by a black arrow of normalized length, caused the recalled target location, portrayed by the red arrow, to be displaced in the same direction, albeit by a smaller magnitude. c) In contrast, following rotation, the recalled target location was displaced in a direction opposite the one required to preserve the distances between the memory items. For illustrative purposes, the displacement of the non-target memory items is represented by the black line and the average displacement of the target items by the red line.*

from the two non-target items. If the latter interpretation is correct, then displacing the non-target memory items' position by rotation at the time of recall should result in an identical rotation of the recalled target location. Participants instead recalled the target location at a position rotated by 0.11^0 in the direction opposite the one used to displace the non-target memory items (Fig. 2.3c). These findings suggest that participants did not simply memorise the relative distance between the items held in memory, but rather they encoded and recalled the position of the memory items in a reference frame centred on CM. This strategy is perhaps automatic, since participants were not informed that the non-target items' location at recall might be displaced. Moreover, enquiry after completing the experiment revealed that participants had failed to notice that the location of non-target items was occasionally changed at recall.

2.4.4 Further evidence for multiple reference frames based memory representations

To further examine the effect of target location and configuration of the memory items on recall, we changed the display's aspect ratio in experiment 3, thus modifying the distance between display boundaries and the target. In addition, we examined the effects of providing information about the memory configuration by presenting the non-target memory items at recall. The memory items were bright discs of uniform hue. The recall display contained the two non-target items, if the sample display had contained three items, or nothing, if the sample display had contained only one item (Fig. 2.4a). The native aspect ratio of the display (44.76^0 x 25.84^0) was used, resulting in targets being farther away from boundaries along the display azimuth than elevation. Both memory load and target location affected the variable error (See Supporting data for relevant statistics). The variable error along elevation showed a modal relation with target location, similar to the one in experiment 1, being largest for targets at locations intermediate between the display centre and boundaries. However, along azimuth, the variable error increased monotonically with increasing target

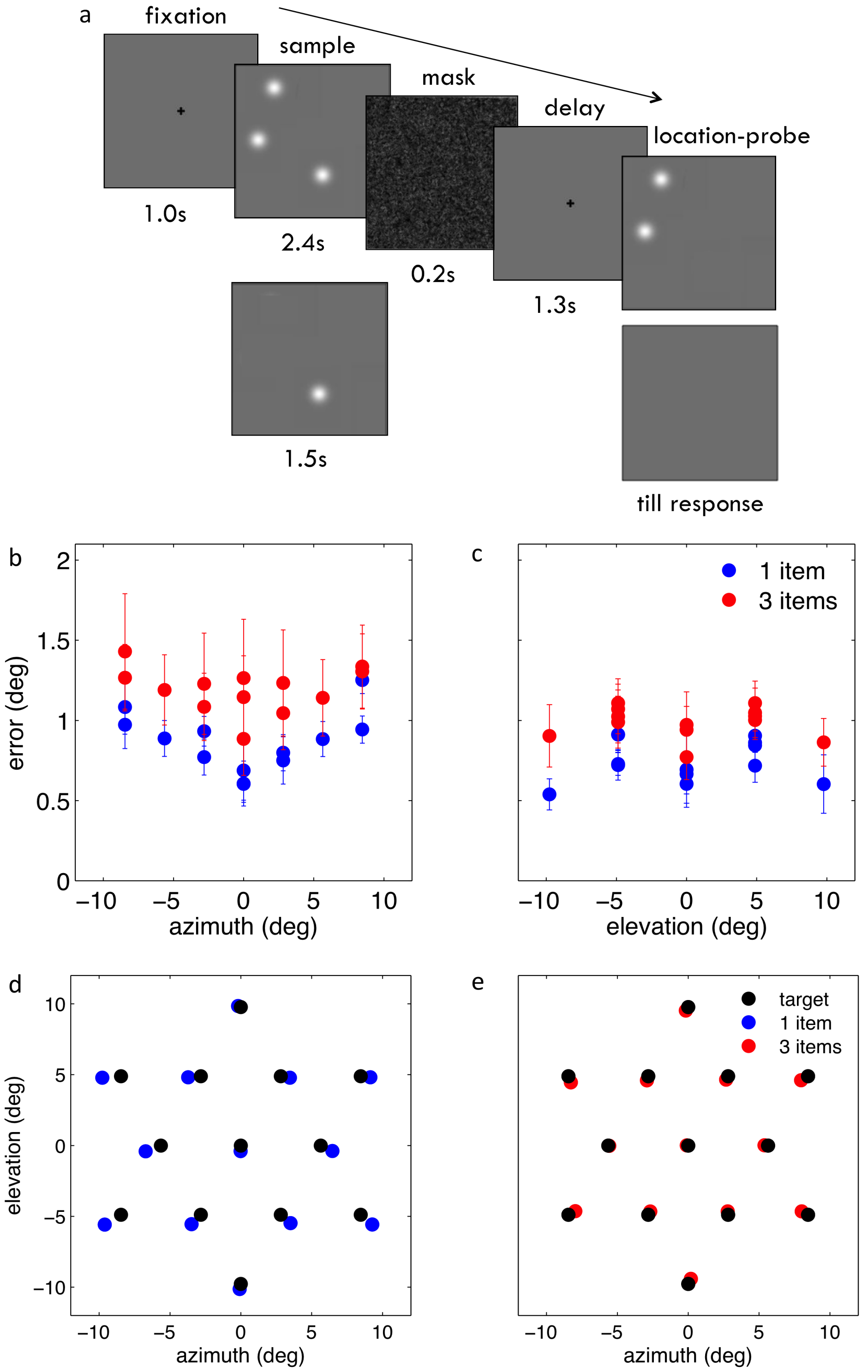

Figure 2.4: *Location-probe diminishes the effects of memory load on recall. a) Trial structure. When the memory load was three, the target to be recalled was identified by highlighting the location of the two non-target items. When the memory load was one the appearance of the cursor*

indicated the beginning of the recall period. b) The error standard deviation is shown as a function of target azimuth, when the memory load is one (in blue) and three (in red), and c) as a function of target elevation. Along azimuth, the variable error increases monotonically with target eccentricity. Along elevation, however, the variable error shows a peak at eccentricities intermediate between the display centre and its boundaries. d) Recalled targets were systematically displaced outward and downward (in blue) relative to their location in the sample display (in black) when the memory load was one, e) while they were displaced toward the centre of the display when the memory load was three (in red). (see also Figs. 2.6Sa-c).

eccentricity, suggesting that recall error reflects the target's proximity to visual landmarks, such as the display boundaries (Fig. 2.4b,c). The patterns of systematic errors were similar to those observed in experiment 1 (Fig. 2.4d,e; see also Figs. 2.6Sa-c; see Supporting data for relevant statistics).

We also found that the effect of memory load on recall precision was diminished - the ratio of the errors' standard deviations when the memory load was three and one, respectively, was 1.38 for azimuth, (95% CI = 1.26-1.49) and 1.36 for elevation (95% CI = 1.26-1.46). The diminished effect of memory load on precision suggests that non-target memory items, when shown at recall, may act as landmarks.

2.4.5 Improved spatial recall reflects recall rather than encoding strategies

The diminished effect of memory load, when the non-target memory items were presented at recall may be confounded by differences in the display layouts and target locations used in experiments 1 and 3. In experiment 4, we compared the effects of the two recall procedures. The sample display contained three memory items and, at the time of recall, the target was identified, in separate blocks, either by its colour or by presenting the non-target items. The display layout and the location of the memory items were the same in the two recall conditions (Fig. 2.5a). When the target was identified by the non-target items' locations, the standard deviation of the recall error was greater than when the target was identified by its colour, both for target azimuth ($F(1,5) = 26.11$, $p = 0.004$) and elevation ($F(1,5) = 14.05$, $p = 0.013$). Interestingly, the recall error also showed a significant interaction between recall procedure and target location along azimuth ($F(11,55) = 2.04$, $p = 0.042$), but not elevation ($F(11,55) = 1.65$, $p = 0.109$), the difference between error sizes being largest for target locations intermediate between the centre and the boundaries of the display (Figs. 2.5b,c). This observation suggests that the presence of non-target items at recall improves precision more prominently for targets farthest from landmarks. The most obvious interpretation of this trade-off is that memory items, shown at recall, act as vicarious landmarks. We also observed smaller systematic recall errors when the recall probe was the non-target items than the target colour, although the patterns of errors were similar (Figs. 2.5d,e; see also Figs. 2.7Sa,b; see Supplemental data for relevant statistics).

An alternative explanation for the effects of probing procedure on recall is that the demands of remembering the colour of the memory items, in addition to their location, may increase the memory load when the probe is the target colour and thus contribute to the differences observed between the two probing procedures. This explanation appears unlikely given that different dimensions of the visual stimulus, such as position and colour, are thought to be encoded using independent memory resources (Bays et al., 2011; Wheeler & Treisman, 2002). A perhaps more plausible hypothesis is that participants could have used different encoding strategies depending on the probe used to identify the target at recall. For example, observers may have memorised only the average location of the memory items' configuration, when the location-probe was used, since a simple computation would then yield the location of the target item at recall. In experiment 5, we controlled for these potential confounds by mixing

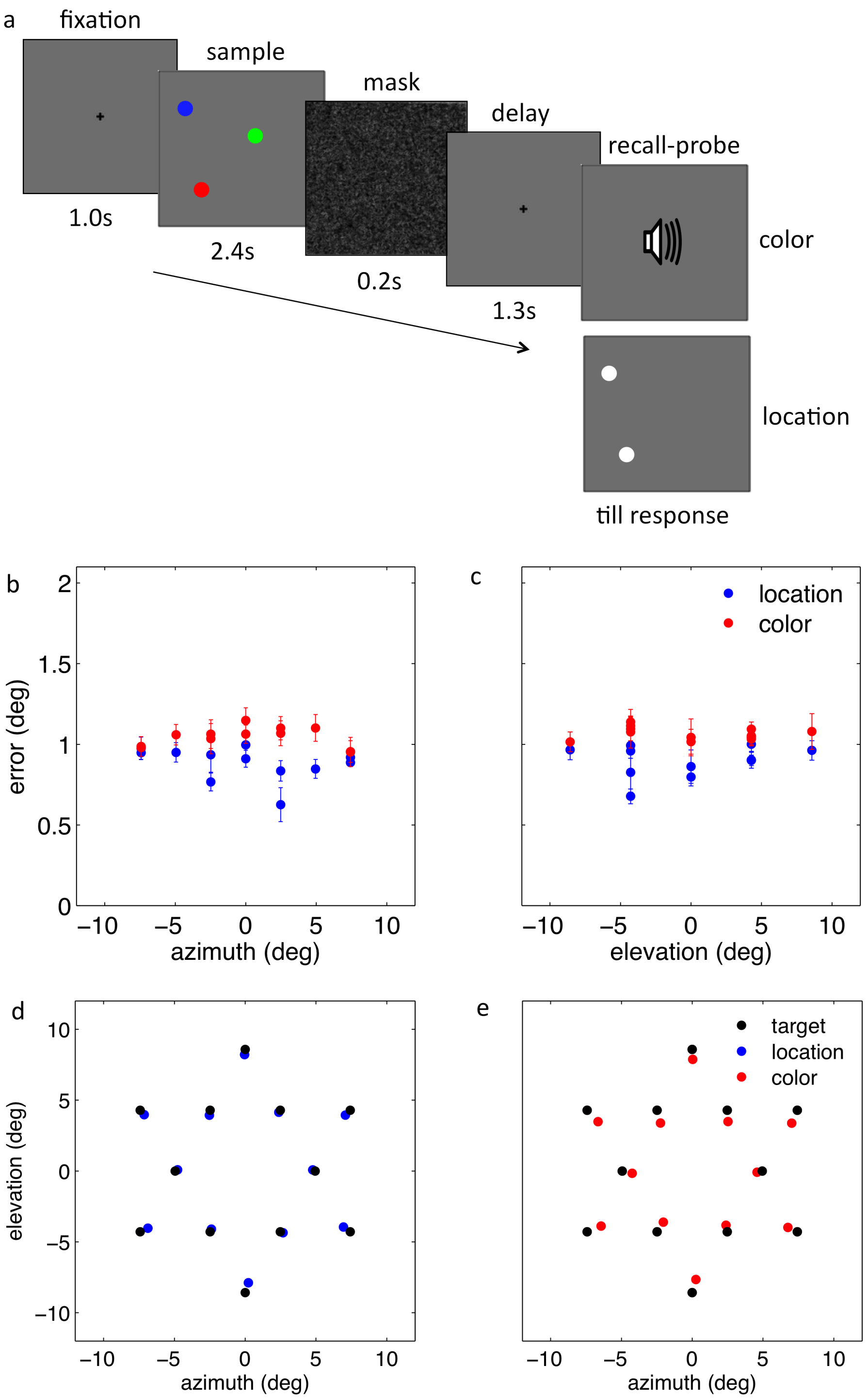

Figure 2.5: *Probing procedure affects spatial recall. a) Trial structure. The target to be recalled was identified either by presenting the non-target items (location-probe), or by voicing the target colour (colour-probe). The memory load was always three. b) The error standard deviation is shown as a function of target azimuth, following location (in blue) and colour-*

probes (in red), and c) as a function of target elevation. Variable error was smaller for the location than the colour-probe condition. This difference was largest for targets halfway between the centre and the boundaries of the display. d) Following location-probes, participants underestimated the target distance from the centre of the screen less prominently than e) following colour-probes. (see also Figs. 2.7Sa,b; Figs. 2.8Sa-d, Figs. 2.9Sa,b).

probes in the same blocks. Since the participants could not anticipate which recall probe would be used, they had to remember both the location and colour of the memory items in every trial, thus minimising the possibility that memory load or encoding strategies could contribute to performance differences between probing procedures. We observed smaller variable and systematic errors in the location than the colour-probe condition (Figs. 2.8Sa-d and S4a,b; see Supplemental data for relevant statistics), as in the previous experiment, suggesting that the probe effects arise at recall rather than reflecting changes in encoding strategies.

2.4.6 Supplemental results

2.4.6.1 Experiment 2

Two-way, repeated-measures ANOVAs, revealed a significant effect of target location (azimuthal - $F(12,36) = 6.73$, $p < 0.001$; elevation – $F(12,36) = 3.93$, $p = 0.001$), and a significant interaction between target location and memory load (azimuthal - $F(12,36) = 2.89$, $p = 0.007$; elevational - $F(12,36) = 2.02$, $p = 0.052$). However, no main effect of memory load was found (azimuthal - $F(1,3) = 3.83$, $p = 0.145$; elevational - $F(1,3) = 7.05$, $p = 0.077$; Figs. 2.4b,c).

Two-way, repeated-measures ANOVAs showed a significant effect of target location (azimuthal - $F(12,36) = 2.90$, $p = 0.007$; elevational - $F(12.36) = 0.18$, p

= 0.999), but no significant effect of memory load (azimuthal - $F(1,3) = 0.31$, $p = 0.615$; elevational - $F(1,3) = 4.34$, $p = 0.129$) on systematic error. A significant interaction between target location and memory load (azimuthal - $F(12,36) = 23.10$, $p < 0.001$; elevational - $F(12,36) = 17.40$, $p < 0.001$; Figs. 2.4d,e).

Reparametrizing the linear component of error in terms of tensors showed a significant memory load effect on the error divergence, namely the tendency to overestimate/underestimate the target distance from the display centre ($t(3) = 7.78$, $p = 0.004$), as in experiment 1 (Fig. 2.6Sa). The systematic recall errors in CS and CM coordinates were broadly similar to those found in experiment 1 (Figs. 2.6Sb,c). One sample t-tests showed that the target azimuth, but not elevation, was overestimated in CS coordinates (azimuth - $t(3) = 4.14$, $p = 0.026$; elevation - $t(3) = 1.91$, $p = 0.153$), when the memory load was one. When the memory load was three, one sample t-tests showed no significant systematic error in CS coordinates (azimuth - $t(3) = 1.30$, $p = 0.286$; elevation - $t(3) = 2.16$, $p = 0.119$), and a marginally significant underestimation in CM coordinates along elevation only (azimuth - $t(3) = -1.91$, $p = 0.152$; elevation - $t(3) = -2.93$, $p = 0.061$).

2.4.6.2 Experiment 4

The systematic recall errors were diminished when a location probe was used compared to a colour probe. There was no significant main effect of probing procedure (azimuth - $F(1,5) = 2.63$, $p = 0.166$; elevation - $F(1,5) = 3.56$, $p = 0.118$). There was a significant effect of target location (azimuth - $F(11,55) = 11.19$, $p < 0.001$; elevation - $F(11,55) = 17.25$, $p < 0.001$), as well as a probing procedure by target location interaction (azimuth - $F(11,55) = 3.93$, $p < 0.001$; elevation - $F(11,55) = 9.13$, $p < 0.001$; Figs. 2.5d,e). Paired-samples t-tests showed that probing procedure significantly affected only the divergence of the error fields ($t(5) = 3.08$, $p = 0.027$), the distance of the target from the display

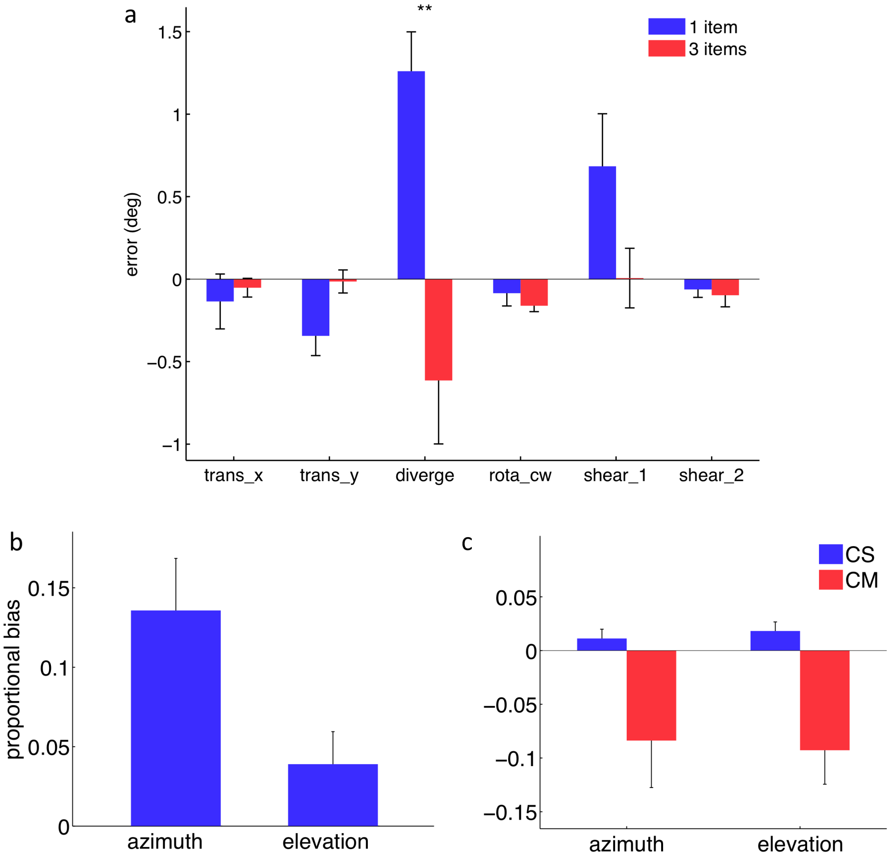

Figure 2.6S: *Memory load effects on systematic error. a) Memory load only affected the divergence of the error field. b) Proportional recall bias in centre of screen (CS) coordinates (in blue) when the memory load is one. c) Proportional recall bias in CS (in blue) and centre of the memory items' configuration (CM) coordinates (in red) when the memory load is three. Target azimuth and elevation, in CS coordinates, was overestimated both when the memory load was one and three. In addition, when the memory load was three, participants underestimated both target azimuth and elevation in CM coordinates. trans - translation, diverge - divergence, rota_cw - clockwise rotation. **$p < 0.01$.*

centre being underestimated more following the colour than the location probe (Fig. 2.7Sa).

A two-way, repeated-measures ANOVAs showed that the recall error was

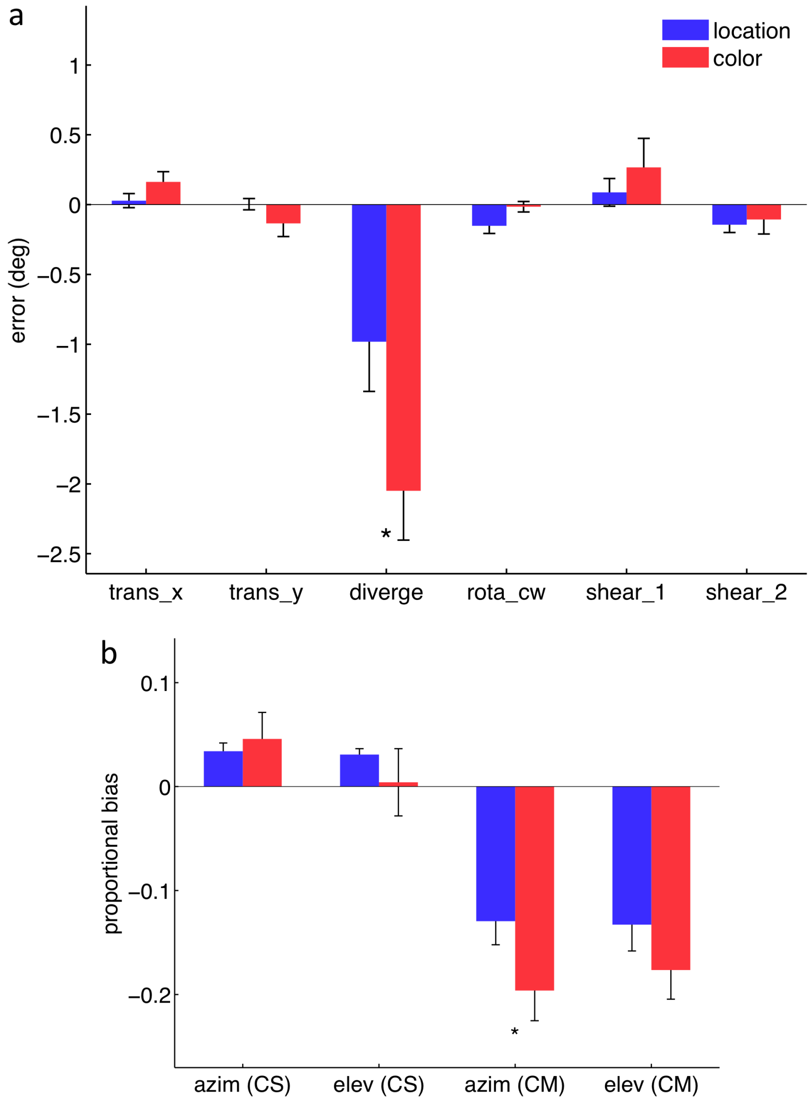

Figure 2.7S: *Probing procedure effects on the systematic error. a) Probing procedure only affected the divergence of the error field. b) Proportional systematic bias in screen (CS) coordinates along azimuth and elevation, and centre of memory items' configuration (CM) coordinates along azimuth and elevation following location (in blue) and colour-probes (in red). Target azimuth, in CS coordinates, was overestimated whether the probe was location or colour. Along the azimuth, significantly smaller displacements of the recalled target locations towards the CM were observed following location than colour-probes. trans - translation, diverge - divergence, rota_cw - clockwise rotation, azim - azimuth, elev - elevation. *p < 0.05.*

significantly affected by probing procedure (azimuth - F(1,5) = 10.10, p = 0.025; elevation - F(1,5) = 10.40, p = 0.023) and reference frame (azimuth - F(1,5) = 33.91, p = 0.002; elevation - F(1,5) = 26.77, p = 0.004) (Fig. 2.7Sb). The probing procedure by reference frame interaction was not significant (azimuth - F(1,5) = 5.58, p = 0.065; elevation - F(1,5) = 0.09, p = 0.777).

2.4.6.3 Experiment 5

Two-way, repeated-measures ANOVAs showed no significant effect of the probing procedure (azimuth - F(1,9) = 0.23, p = .643; elevation - F(1,9) = 0.30, p = 0.598), but a significant effect of target location (azimuth - F(12,108) = 3.58, p < 0.001; elevation - F(12,108) = 6.46, p < 0.001), and probing procedure by target location interaction (azimuth - F(12,108) = 2.66, p = 0.004; elevation - F(12,108) = 2.06, p = 0.025) on the recall error standard deviation (Figs. 2.8Sa,b). The systematic recall errors were smaller following the location probe (Figs. 2.8Sc,d). Two-way, repeated-measures ANOVA showed no significant effect of probing procedure (azimuth - F(1,9) = 4.19, p = 0.071; elevation - F(1,9) = 3.92, p = 0.079), but a significant effect of target location (azimuth - F(12,108) = 14.26, p < 0.001; elevation - F(12,108) = 37.72, p < 0.001), and a significant interaction of probe by target location (azimuth - F(12,108) = 2.66, p = 0.001; elevation - F(12,108) = 3.66, p < 0.001). Paired-samples t-tests showed a significant probe effect on the divergence of the systematic error field (t_9 = 2.26, p = .050), which was smaller following the location than colour probe (Fig. 2.9Sa).

The systematic errors in CS and CM coordinates showed a significant effect of probe (azimuth - F(1,9) = 20.66, p = 0.001; elevation - F(1,9) = 8.54, p = 0.017), reference frame (azimuth - F(1,9) = 10.31, p = 0.011; elevation - F(1,9) = 4.10, p = 0.073) and probe by reference frame interaction (azimuth - F(1,9) = 16.55, p = 0.003; elevation - F(1,9) = 7.93, p = 0.020), the error in CM, but not CS, coordinates being much smaller following location than colour probes (Fig.

2.9Sb).

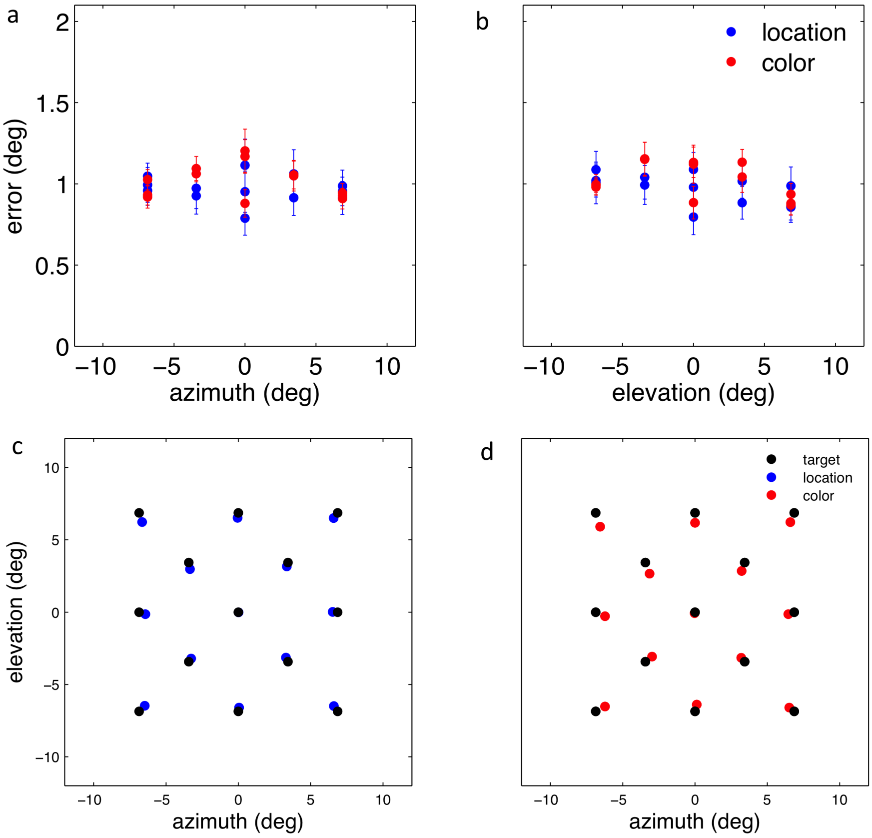

Figure 2.8S: *Probing procedure effects on spatial recall in mixed-probe blocks. a) The error standard deviation is shown as a function of target azimuth, following location (in blue) and colour-probes (in red), and b) as a function of target elevation. The variable error was smaller following location than colour-probes. This difference was largest for targets between the centre and the boundaries of the display. c) Following location-probes, participants underestimated the target distance from the centre of the screen less prominently than d) following colour-probes.*

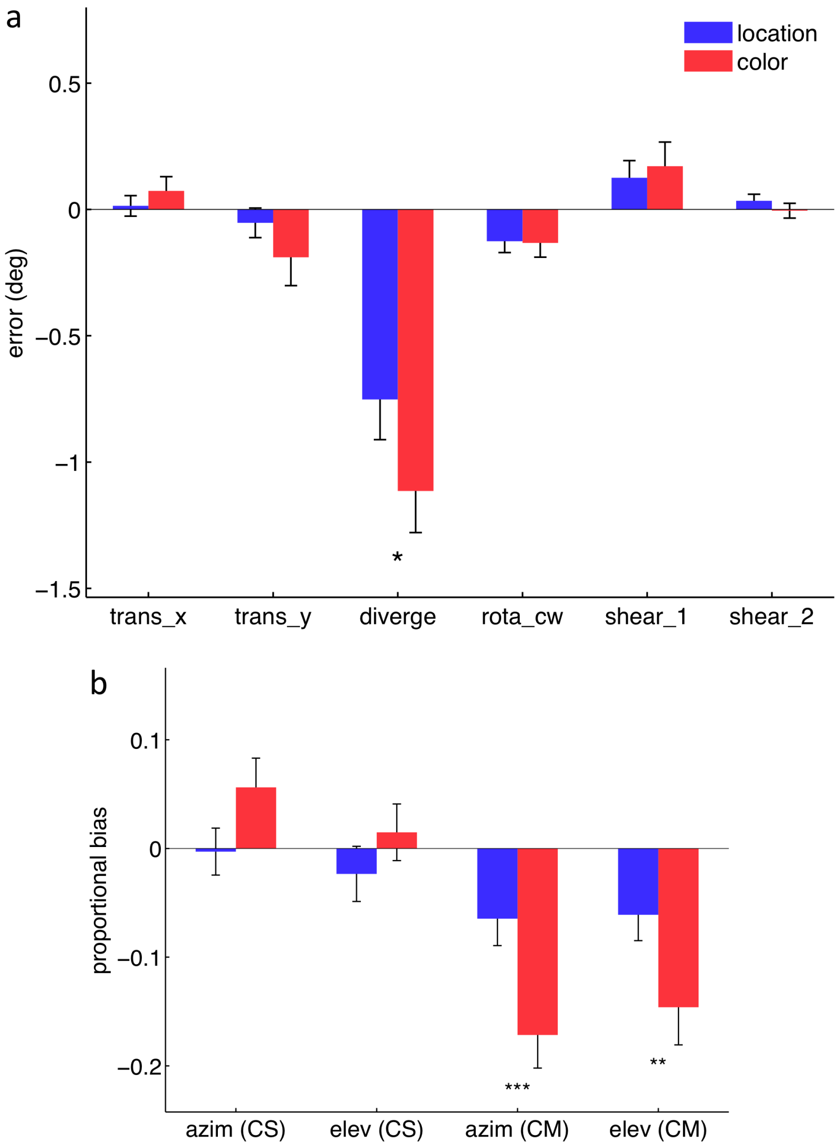

Figure 2.9S: *Probing procedure effects on the systematic error in mixed-probe blocks. a) Probing procedure only affected the divergence of the error field. b) The proportional systematic bias in screen (CS) and centre of memory items' configuration (CM) coordinates, along azimuth and elevation, is shown following location (in blue) and colour-probes (in red). Along azimuth as well as elevation, significantly smaller displacements of the recalled target locations towards the CM were observed following the location than the colour-probe. trans - translation, diverge - divergence, rota_cw - clockwise rotation, azim - azimuth, elev - elevation. **$p < 0.01$, ***$p < 0.001$.*

2.5 Discussion

2.5.1 Local level spatial representations determine recall precision

Recent vWM models have assumed that visual information is stored in buffers of limited resolution that may be specific for an object's feature dimensions, be its colour (Zhang & Luck, 2008), orientation or location (Bays & Husain, 2008), but are otherwise not tuned to particular features within a dimension, for example red vs. blue in the case of colour. Accordingly, the ability to recall precisely the colour of a target, its orientation or location should not further depend on its specific colour, orientation or location. However, we found that the precision of spatial recall was significantly modulated by target location and, even more importantly, that memory load scaled multiplicatively the magnitude of the recall error at each of the target locations. Because target location and memory load interact, rather than exert independent, additive effects on recall error, we conclude that the precision of spatial recall depends on the resolution of spatially tuned mechanisms, instead of mechanisms that generalise over space.

An alternative explanation that could be put forth to explain the multiplicative interaction between the memory load and target location is that these effects arise at the perceptual level due to increase in perceptual noise with increasing number of items. This seems unlikely, as our participants were encouraged to foveate each individual item during the encoding phase and the sample display was visible long enough to render that possible. Furthermore, if the memory load effects observed are perceptual in nature, decreasing the perceptual noise by increasing the duration of the display during encoding should decrease the memory load effects. However, previous studies have shown that memory load effects are largely independent of the display duration (Luck & Vogel, 1997; Zhang & Luck, 2008). Also, increasing the delay interval between encoding and recall should have no effect on the recall error, if these effects are perceptual in nature. Contrary to this prediction, Sheth and Shimojo (2001) showed that the recall error of a target location towards a visually salient landmark systematically increases with increasing delay interval. Considering all these, a perceptual explanation of the effects observed in our study seems unlikely.

The effects of target location suggest that proximity to landmarks, whether the boundaries or the centre of the display, improved recall precision. In fact, when the vertical boundaries of the display were displaced outwards, thus increasing their distance from the most eccentric targets, these targets were recalled less precisely than targets at intermediate positions. Finally, an improvement in recall precision was observed particularly for targets that were farthest from both centre and the boundaries of the display, when non-target memory items were presented at recall suggesting that they acted as vicarious landmarks. Visual landmarks have been found to improve the localization of nearby visual targets under conditions in which perceptual rather than memory constraints were examined (Fortenbaugh, Sanghvi, Silver, & Robertson, 2012), suggesting perceptual and memory representations, which guide target localization, are largely shared. This inference is in keeping with recent functional imaging data concerning the neurophysiological underpinnings of visual short term memories in humans, which demonstrated that distributed, voxel-wise patterns of BOLD signals in early Visual cortical regions, recorded while participants maintained visual data in memory, convey information about memorised stimuli (Lee et al., 2013; Serences et al., 2009). Our behavioural data, in contrast to current vWM models, are consistent with this neurophysiological evidence because they indicate that vWM utilises spatially tuned processes similar to those used during the analysis of the sensory input in Visual cortex.

An issue of significant theoretical interest is why the resolution of local representations of visual data should be liable to the effects of memory load. Specific, though speculative, proposals have been put forth by others, including the suggestion that the spatial resolution may be limited by within receptive field interactions among closely spaced memory items (Delvenne, 2005; Franconeri, Alvarez, & Cavanagh, 2013) or population level normalization of neural activity in cortex (Ma, Husain, & Bays, 2014).

2.5.2 Global spatial representations anchor local data to stimulus configuration

Local visual representations seem to account for the effects of target location on recall precision. However, we also found that interactions among the elements that make a visual scene affect recall accuracy. These effects do not seem to be spatially limited, but rather increase with their distance from the recalled target (Hubbard & Ruppel, 2000). When the observers had to remember only one item, the recalled target location was displaced eccentrically, that is away from the centre of the display. However, when three items had to be remembered, the recalled target location was displaced toward, rather than away from centre of the display. The direction change of the recall bias with memory load was found to reflect two linearly independent distortions. The first was a hypermetric bias in display coordinates, which solely determined the nature of the systematic error when one item was memorised, and a hypometric bias toward the centre of the memory items' configuration, which dominated the systematic error when three items were memorised. However, the persistence of the hypermetric bias in screen coordinates when three items were held in memory, suggests separate causes for the hypermetric and hypometric biases. Hence, we suggest that spatial memory depends on representations which employ separate reference frames, one in display coordinates and the other relative to the centre of the set of memorised elements. Other interpretations of the hypometric bias are not particularly plausible. For example, it is possible that participants may have occasionally reported the location of a non-target memory item, giving the impression that the recalled location of the target was displaced, when averaged over trials, toward the centre of the memory items' configuration. However, we excluded from the analysis trials in which the recalled location was closer to one of the non-target memory items than the target. Moreover, when the recall display contained two of the memory items, the target was still recalled toward the centre of the memory items' configuration, albeit by a diminished amount, indicating that when the proportion of binding errors was minimised, analytically or by the probe procedure used to identify the target, the hypometric bias in memory coordinates persisted. However, the most conclusive evidence was provided by the finding that translating the non-target items at recall caused a parallel translation of the recalled target location by a similar amount, a finding that simply cannot be explained by participants confounding target with non-target items. A second hypothesis one may entertain, is that the location of the memory items is coded in relative terms, namely that observers keep track of the distance between items in memory rather than their location in relation to some other reference. If this were the case, then any rigid displacement of the non-target memory items should result in displacement of the recalled target to preserve the overall configuration. However, when we displaced the non-target memory items at recall, by rotating their position around an axis passing through the centre of the display and orthogonal to the image plane, the recalled target location was not displaced in the direction that would have preserved the distance between the target and non-target items, but rather in the opposite direction. This finding fundamentally undermines the view that observers were memorising the distance between the target and non-target memory items, and supports instead the interpretation that the target position is coded and recalled relative to a common reference frame, namely the centre of the memory items' configuration. Thirdly, it has been suggested that configurational effects on recall may be best understood within a Bayesian framework (Brady & Alvarez, 2011; Brady, Konkle, & Alvarez, 2011). Accordingly, the configuration of the memory array is used to generate a prior for the distribution of the possible target positions, which, combined with noisy estimates of the actual target position, leads to target recalls biased toward the average position of the memory items. This proposal would predict an increase in centripetal bias whenever information about the memory configuration is provided. However, we found that presenting the non-target items at recall diminishes the centripetal bias. Single unit data in higher order Parietal areas of behaving primates have indicated that in a match to sample task, visually evoked responses to previously seen dot stimuli are largely invariant to parallel displacements of the stimulus over the retina, suggesting a stimulus centred coding of complex spatial configurations (Chafee et al., 2005; Chafee, Averbeck, & Crowe, 2007), such as those that may underpin the behavioural effects summarized above. The maintenance of the configuration of memory arrays in higher order regions could also account for the finding that the complexity of the memory array scales the amplitude of delay period activity in Parietal and Frontal regions during vWM tasks (Todd & Marois, 2005; Vogel & Machizawa, 2004).

In conclusion, both behavioural and neurophysiological data are consistent with the idea that there are at least two representations of spatial data in vWM - one where fine spatial details are maintained by spatially curtailed mechanisms in early Visual cortex, the other where summaries of the global configuration are maintained by mechanisms that generalise over space in higher cortical areas.

2.5.3 Do configurational effects arise only at encoding or also at recall?

Configurational effects in vWM are assumed to arise at the encoding stage as they are believed to reflect the consequences of perceptual grouping and gestalt effects (Brady et al., 2011; Ma et al., 2014). However, when non-target memory items are shown at recall, there is an improvement in accuracy and a diminished centripetal bias. Moreover, when non-target memory items were translated at recall, the recalled target location was also displaced in parallel direction. These findings indicate that configurational effects do not arise only at encoding but also at recall. One may therefore speculate that the same spatial updating mechanisms that characterise the positional invariances of Parietal neurons mentioned above also characterise recall processes in human participants (Chafee et al., 2005; 2007).

Chapter 3: The effects of learnt landmarks on recall from spatial working memory are consolidated by sleep

3.1: Abstract

Long-term memory (LTM) facilitates either encoding or recall from working memory (WM). An early view suggests that overlearnt spatial representations optimise efficient recall. Alternatively, learnt environmental regularities may be used to optimise encoding. To tease these accounts apart, we compared the effects of learnt items encoded in WM and landmarks presented at recall in a spatial WM (sWM) task. Moreover, given the potential role of sleep in learning spatial layouts, we examined its effects on learning and consolidation. In the learning session, participants reported the location of one of two memory items. One of the memory items was presented at a fixed location over trials, while the other varied. The landmark was presented in the sample and recall display at a fixed position. In test sessions, a single memory item was shown in the sample display, whose location varied over trials. The landmark was presented only at recall. During the learning session, targets close to the fixed-memory item or the landmark were recalled more precisely and accurately. Following learning, targets close to the landmark, but not the fixed memory item, were recalled more accurately, specifically when the learning block was followed by sleep. There was no localized change in recall precision or generalised improvement in recall accuracy and precision over test sessions. We conclude that LTM assists WM by maximising the retrieval of stored information rather than its efficient encoding. Moreover, sleep is required for consolidation of local landmark in LTM.

3.2 Introduction

Working memory (WM) is thought to comprise a set of cognitive operations essential for sustaining goal directed behaviour over time (Baddeley & Hitch, 1974). However, its storage mechanisms are characterised by finite capacity and slow recall times for information held therein. These limitations can impede the deployment of other cognitive processes, such as attention (Awh, Vogel, & Oh, 2006). It has been suggested that various strategies are used to overcome WM limitations. One viewpoint is that information stored in long-term memory (LTM) can be referenced by WM, thus providing a shorthand code useful for minimising the memory load (Brady & Alvarez, 2011; Ericsson & Kintsch, 1995). An alternative viewpoint is that when information stored in WM is encoded in relation to cognitive maps held in LTM, its retrieval is facilitated by reference to known landmarks (Cicero, 1954; Yates, 1992). These two proposals differ: the former emphasises the possibility to increase the amount of information retained by exploiting efficient coding mechanisms, while the latter to recover relevant information at recall.

Clearly, which if any procedure can be used to improve storage and recall of information held in WM greatly depends on the nature of WM limitations. Traditionally, both verbal and visual WM storage have been thought to encompass a limited number of slots (Cowan, 2010). However, there has been disagreement regarding the units of storage. One possibility is that objects are stored as unitary constructs, and that only as many objects as there are slots can be maintained in WM at any given time, since each slot can accommodate information about a single word or object and no more (Luck & Vogel, 1997). Recently, measurements of recall precision as a function of memory load suggested either that slots in visual and spatial WM have limited resolution or that WM relies on a limited resolution resource, rather than slots, which is divided among memorised features, such as the colour, orientation or shape of items held in WM (Bays & Husain, 2008; Bays et al., 2011). Since there is no evidence, so far, that when participants recall familiar versus unfamiliar scenes recall precision is any different, it seems that LTM may not by itself improve encoding of the fine details of a visual scene into WM (Brady, Konkle, Gill, Oliva, & Alvarez, 2013). In fact, while manipulations of memory load have consistently been found to change the precision of recall, the only manipulation found to improve recall precision so far is when incomplete samples of the memory array are presented at recall and participants report the missing element (Katshu & d'Avossa, 2014). Greater recall precision is observed under these conditions than when no sensory information about the memory array is made available at recall. Therefore, individual visual features are likely coded relative to other elements in the array, facilitating recall when the latter become visible. One interpretation of this finding is that items shown at recall act as landmarks. However, It is not entirely clear how to reconcile this conclusion with the view that a limited resolution resource is divided among independent representations, one for each element of a memory array. Moreover, the observations that fine visual features of items held in WM can be decoded from voxel-wise patterns of BOLD activity in retinotopic areas of human cortex and that the precision of spatial recall varies systematically with the position of the memory target in the scene are both in keeping with local, spatially curtailed, memory representations and, more generally, the idea that features belonging to different objects are coded independently (Katshu & d'Avossa, 2014; Serences et al., 2009). To reconcile these apparently contradictory evidences regarding the representation of multi-elemental displays in WM, it has been suggested that either information is coded in different spatial scales and reference frames, or that interactions between elements can arise in retinotopic maps through lateral connections akin to those mediating contrast normalization (Katshu & d'Avossa, 2014; Ma et al., 2014).

One aspect of WM recall consistent with resource-based models is binding errors. These errors occur when the feature of an element other than the target is recalled. It is plausible to infer from such mistakes, that a feature belonging to a different element, also held in memory, is incorrectly bound to the recall target by an active, error prone process. If so, then binding features held in memory to the objects they belonged to, is not a foregone aspect of the way visual information is stored, contrary to what slots model predicts. One way binding of features may proceed is through the alignment of spatially indexed feature maps with a master map location, providing the handle to sort which features belong to the same object (Treisman, 1998; Wheeler & Treisman, 2002). The idea that space may facilitate the encoding and retrieval of complex information in memory is far from a novel idea, having already been recognized by ancient students of rhetoric as a useful tool of their trade. In fact, the practical need to memorise large amounts of information spurred political and legal practitioners of the ancient world to devise novel ways to increase the efficiency of human WM. A widely endorsed proposal was that the material to be memorised should be encoded by placing individual items, whether ideas or facts, in halls, rooms and chambers of memory palaces in order to bolster its recall. These imaginary structures, which could replicate the layout of actual buildings, had to be familiar to the memoriser, through constant rehearsal and mental surveys. Recalling information in an orderly fashion would then simply require navigating the various parts of the palace, where specific bits of information had been previously placed (Cicero, 1954; Yates, 1992).

In order to distinguish between these two accounts of the relation between LTM and WM, namely a probabilistic, statistical model and a referential one, we examined whether participants learnt from repeated presentations of either a memory item whose location had to be recalled or a landmark, which neither had to be recalled nor was predictive of the location of memory items. We reasoned that if recurrent events or statistical dependencies between events are stored in LTM then participants should eventually be better at recalling the position of a target near a location where it is frequently encountered, but would not be better at recalling the location of a target near the location of uninformative landmark, if it is not predictive of the location of memory items that are recalled. On the other hand, if long-term spatial memories containing maps of familiar environments and major landmarks therein facilitate the recollection of the location and identity of items of interest, then one may predict that landmarks, which represent a stable feature of the environment, rather than the location of individual memory items would improve the spatial recall of targets in their vicinity.

Finally, an important aspect of memory consolidation is its reliance on neural mechanisms that are prominently, though not only, recruited during sleep and are thought to promote the shaping of neocortical circuits sustaining LTM. The importance of sleep has been demonstrated not only in the acquisition of episodic memories, but also in perceptual learning and skill acquisition. Since all these forms of memories may play a role in improving spatial recall in an over-trained WM task, we systematically examined the role of sleep.

We found that neither accuracy nor precision of spatial recall improved for items appearing at locations that had often been recalled in a previous learning session. However, recall accuracy, but not precision, was higher for items closer than those further from a landmark shown at recall following a learning session where the landmark was shown at the same location both in the sample and recall display. Moreover, this landmark-based improvement in recall accuracy was seen only when the learning session was immediately followed by natural sleep period. We conclude that the main role of LTM in supporting spatial working memory (sWM) is to provide landmarks for facilitating recall. Also, sleep immediately following the learning period consolidates the effect of landmarks on sWM.

3.3 Methods

3.3.1 Participants

The Research Ethics Committee of the School of Psychology at Bangor University approved the experimental protocols. Written informed consent was provided by all the participants before engaging in any experimental procedures. Participants received remuneration for taking part in the study. Thirty-six adult participants (22 females) with a mean age of 23.03 years (s.d. = 7.31 years), who met inclusion criteria, were recruited after screening. The screening included study-specific questionnaires to exclude the presence of major neurological or psychiatric disorders, substance use (excluding nicotine and caffeine) as well as current psychotropic medications, traumatic brain injury, and sleep disorders (Appendices 1 and 2). Participants had normal or corrected-to-normal visual acuity and normal colour vision. Each participant provided a sleep diary, which detailed the customary sleeping schedule and sleeping schedule on the day before and the day of testing (Appendix 3). Participants were advised to abstain from any drug or alcohol use 24 hours prior to the start of testing and to remain so till completion of the final testing session. Participants were also advised to maintain their usual sleep schedule during the testing phase, except that they were not to nap during the day. The adherence of participants to these instructions was assessed at the beginning of each testing session. Participants were randomly assigned to three groups – morning, afternoon, and night – the details of which are given below.

3.3.2 Experimental design

All the participants were tested over three sessions separated by approximately 8-hour-long intervals. The first session included a block in which the position of a single memory item had to be recalled after a short delay. This was followed by a learning block. In the learning block, participants were shown two memory items and a landmark. Trial after trial, the landmark and one memory item appeared at the same locations. The second and third sessions include one block of the same sWM task used to assess baseline performance in the initial session. The latter two sessions did not include the learning block (Fig. 3.1a). The experimental design was geared toward examining 1) whether intensive but time limited exposure to a landmark or a memory item, repeatedly presented at the same locations, would, in subsequent testing, lead to improved recall of targets appearing at nearby locations; and 2) the effect of sleep on spatial learning.

The three groups of participants (morning, afternoon and night) were tested to allow us to disentangle the effects, if any, of learning and sleep on recall. It is important to point out here that the three sessions were equally spaced out in all the three groups. The three groups were tested as described below (Fig. 3.1a).

3.3.2.1 Morning group

The morning group consisted of twelve participants (7 females) with a mean age of 20.83 years (s.d. = 1.12 years). Participants had their first session in the morning, at least half an hour after waking up. This testing schedule ensured that there was no intervening sleep between the three sessions and hence any learning could not depend on sleep-mediated consolidation (Fig. 3.1a).

3.3.2.2 Afternoon group

Twelve participants (7 females) with a mean age of 24.67 years (s.d. = 11.24 years) comprised the afternoon group. The first session of this group took place in the afternoon. The precise timing of the afternoon session was chosen so that the subsequent sessions could be carried out with no or minimal interference with the usual sleep-wake cycle of the individual participants. This testing schedule was designed to assess the effects, if any, of delayed sleep on spatial learning, since sleep took place between the second and third sessions, but not between first and second sessions (Fig. 3.1a).

3.3.2.3 Evening group

The evening group had twelve participants (8 females) with a mean age of 23.58 years (s.d. = 5.84 years). This group had their first session in the evening. Again, the timing of the first session was chosen to minimise conflict with the usual sleep cycle. In this group, sleep took place between the first and second sessions and allowed us to determine the immediate effects of sleep on spatial learning

The three groups did not differ significantly neither in terms of participants‘ age (F(2,33) = 0.87, p = 0.428) or gender ($\chi^2(2) = 0.23$, p = 1.000). Moreover, the habitual sleep duration for the morning group was 7.79 hours (s.d. = 0.67 hours), for the afternoon group 8.03 hours (s.d. = 1.20 hours), and for the evening group 8.20 hours (s.d. = 1.05 hours). The between group difference was not significant (F(2,33) = 0.51, p = 0.606). On the day before testing, the morning group had slept on average for 8.39 hours (s.d. = 1.24 hours), the afternoon group for 7.69 hours (s.d. = 1.66 hours), and the evening group for 8.18 hours (s.d. = 1.07 hours), while on the day of testing the morning group had slept for 6.28 hours (s.d. = 1.49 hours), the afternoon group for 5.55 hours (s.d. = 1.82 hours), and the evening group for 5.00 hours (s.d. = 0.94 hours). The between group differences were not significant for previous day (F(2,33) = 0.86, p = 0.434), and day of testing sleep duration (F(2,33) = 2.33, p = 0.113)

3.3.3 WM tasks

The stimuli and experimental procedures of the WM tasks were coded in Matlab© using a set of freely available routines to facilitate the display and precise timing of presentation of visual stimuli (Brainard, 1997; Kleiner &

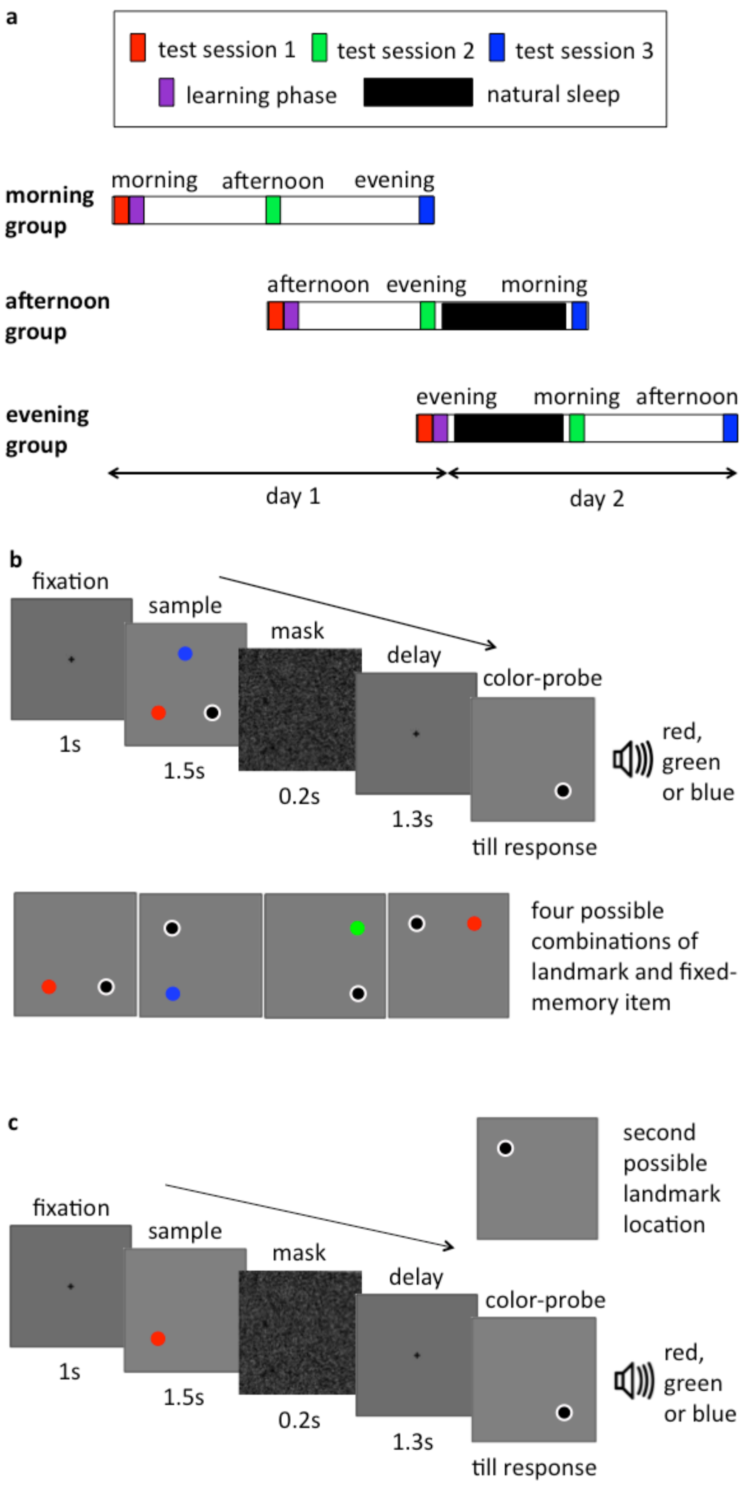

Figure 3.1: *a) Experimental procedure: Participants performed the spatial working memory (sWM) task (test session 1) at the beginning of the study followed by the learning phase. Later, after equally spaced intervals that could involve periods of natural sleep, participants performed the sWM*

task twice (test sessions 2 and 3). b) Learning session: Participants memorised the location of two coloured items presented – one of these memory items occupied a constant location across trials. Also, at the time of encoding a landmark, black dot with white annulus, was presented at a fixed location across trials. Both the fixed-memory item and landmark locations varied over two levels across participants. After a pattern mask and blank interval, the target to be recalled was indicated by its colour. The landmark was presented at the same location during recall as at encoding. c) Test session: Participants memorised the location of the single item presented. After a pattern mask and blank interval, the target to be recalled was indicated by its colour. Also, at the time of recall, a landmark was presented at the previously learnt location, which varied over two levels across participants.

Brainard, 2007; Pelli, 1997). An Apple iMac 10 was used to control the experimental procedures and the display. Stimuli were presented on an LCD monitor (NEC LCD3210). The monitor subtended 25.84^0 x 25.84^0 of visual angle. Head position was restrained by a chin rest, which ensured that the participants kept a distance of 85.0cm from the screen during the experiment.

3.3.3.1 Learning phase

To assess whether repeated exposure to either an item to be encoded in memory or a visual landmark improved spatial recall in later sessions, the first session included a learning block. On consecutive trials, the sample display contained two memory items, either of which would have to be recalled after a short delay, and a landmark that was shown both in the sample and recall display. One of the memory items, the fixed-memory item, and the landmark were presented at the same location. The learning block included three hundred trials. The memory items were coloured circular discs, 0.6° in diameter, presented against a grey background. The landmark consisted of a black circle surrounded by a white annulus, 0.4° in diameter, and was easily distinguishable from the memory items. The position of both the landmark and the fixed-memory item was varied over two levels each, across the participants, in a fully factorial design. The landmark and the fixed-memory item were presented at distance of 3.3° from the display centre along the main diagonal, either in the right lower or left upper quadrants and the left lower or right upper quadrants, respectively, as shown in Figure 3.1b. The other memory item, the variable-memory item, appeared in one of fifteen canonical locations. These were the centre of the screen and locations arranged along two concentric imaginary circles with a radius of 3.3° and 6.6°, respectively, and spaced at 45° intervals in the radial direction. The position of the fixed-memory item and the landmark was jittered, trial to trial, by adding two values obtained by sampling an equally distributed 2D Gaussian distribution with a standard deviation of 0.2°. The variable-memory item location was jittered by sampling a 2D Gaussian distribution with a standard deviation of 0.6°.

Each trial started with a 1.0s long fixation-cross shown at the screen centre. The sample display, containing three stimuli, two memory items and the landmark, was then presented for 1.5s. This was followed by a 0.2s long visual mask. The luminance of each voxel in the mask was generated by sampling a pseudorandom uniform distribution. Following the mask, the fixation-cross appeared at the centre of the screen for 1.3 seconds. Then a computer generated verbal instruction indicated the colour of the memory target whose location had to be recalled. Participants reported the recalled target location by placing a cursor, which had appeared, in the interim, on the screen, along with the previously shown landmark. The cursor and the landmark remained visible until the participant clicked the mouse, which initiated a new trial, after a delay of 0.5 second (Fig. 3.1b).

3.3.3.2 Pre-learning and post-learning test phases

In all the sessions sWM recall was tested using a task that required participants to memorise only one memory item. The trial sequence and memory item position were the same as in the learning block, except that the sample display contained a single memory item and no landmark. The landmark was, however, presented at the time of recall. In session 1, the testing block consisted of 170 trials, while in sessions 2 and 3, 400 trials were collected. Also, in the last two sessions, in 10 trials, presented at random intervals, the participants were asked to report the location of the landmark, rather than the location of the memory item. The landmark was not shown in these trials (Fig. 3.1c).

3.3.4 Data analysis

For each location and session the accuracy and precision of the participants in reporting the target position was estimated using the following procedure. First we estimated the average reported location for each of the seventeen target positions by fitting the following model:

$$\begin{aligned} x_r &= a_0 + a_1 x_t + a_2 y_t + a_0 x_m + a_0 y_m + a_5 x_l + a_6 y_l \\ y_r &= b_0 + b_1 x_t + b_2 y_t + b_0 x_m + b_0 y_m + b_5 x_l + b_6 y_l \end{aligned}$$

where x_r and y_r are the recalled horizontal and vertical coordinates of the target, respectively. x_t, x_m and x_l are the horizontal coordinates of the memory target, the other memory item and the landmark. y_t, y_m and y_l are the vertical coordinates of the memory target, the other memory item and the landmark.

By substituting the canonical coordinates of the target, fixed-memory item and landmark in the equation above, the recalled target location corresponding to each of the seventeen canonical target locations was estimated. The variable error for each target location was estimated by first fitting a model similar to the one above, but which did not include the landmark and memory item coordinates. The residuals were then ordered and their probit score computed from their rank *r*, using the following transformation:

$$z(res_i) = \sqrt{2} \cdot erf^{-1}(2p_i - 1)$$

$z(res_i)$ is the *z* score of the *i*th residual, and p_i is its rank score, computed using the following formula:

$$p_i = \frac{r_i}{1+n}$$

where *n* is the number of trials. The standard deviation of the error was estimated using a linear regression, computed from those residuals whose z-score was comprised in the closed interval [-2, 2]:

$$res = c_o + c_1 \cdot z$$

All group level hypotheses testing examining the effects of target, fixed-memory item and landmark locations, session and group schedule on recall accuracy and precision was carried out using mixed ANOVAs.

3.3.4.1 Memory item and landmark effects on target recall

In order to examine the nature of the interactions between the recalled target, fixed memory item and landmark, we modelled the recalled location as having a linear dependency on the target location on the screen and a power relation with its location in landmark and fixed memory item centred coordinates. The model used to estimate these effects assumed that landmark and memory item either attracted or repulsed the target:

$$x_r = a_0 + a_1 x_t + a_2 \text{sgn}(x_t - x_l) \cdot \text{abs}(x_t - x_l)^{a_4} + a_5 \text{sgn}(x_t - x_l) \cdot \text{abs}(x_t - x_l)^{a_6}$$
$$y_r = b_0 + b_1 y_t + b_2 \text{sgn}(y_t - y_l) \cdot \text{abs}(y_t - y_l)^{b_4} + b_5 \text{sgn}(y_t - y_l) \cdot \text{abs}(y_t - y_l)^{b_6}$$

The model parameters were estimated using a non-linear least square procedure.

3.4 Results

Spatial recall performance of the participants was computed in the form of systematic and variable components of the recall error. Systematic error is the component repeated over trials and was computed as the difference between recalled and actual target locations. The error component that varies from trial to trial is the variable error and was computed as the root square of the mean squared difference between recalled and actual target locations, after removing any systematic difference. Recall accuracy and precision are the reciprocal values of systematic and variable errors, respectively.

3.4.1 Landmark and fixed-memory item improve recall precision during learning

To assess whether the landmark and/or the fixed-memory item, presented at a fixed location across trials, were utilised or learnt by participants, we measured the precision of recall of the variable-memory item, whose position varied trial to trial, during the learning phase of first session (Fig. 3.1b). Figures 3.2a and b show that landmark decreased the standard deviation of recall variable error. Targets in the proximity of landmark were recalled more precisely than targets farther from it. Mixed-model ANOVAs showed a significant interaction between landmark and target position along both azimuth ($F(11,264) = 4.428$, $p < 0.001$) and elevation ($F(11,264) = 6.339$, $p < 0.001$). These findings confirm that participants utilised landmark to encode and retrieve variable-memory item position. Figures 3.2c and d show that fixed-memory item affected the recall variable error in the same way as landmark: specifically, targets closer to fixed-memory item were recalled more precisely. Mixed-model ANOVAs showed a significant interaction between fixed-memory item and target position along azimuth ($F(11,264) = 3.235$, $p < 0.001$) as well as elevation ($F(11,264) = 3.594$, $p < 0.001$). As the fixed-memory item was present only during encoding, these results show that participants learnt and utilised fixed-memory location to

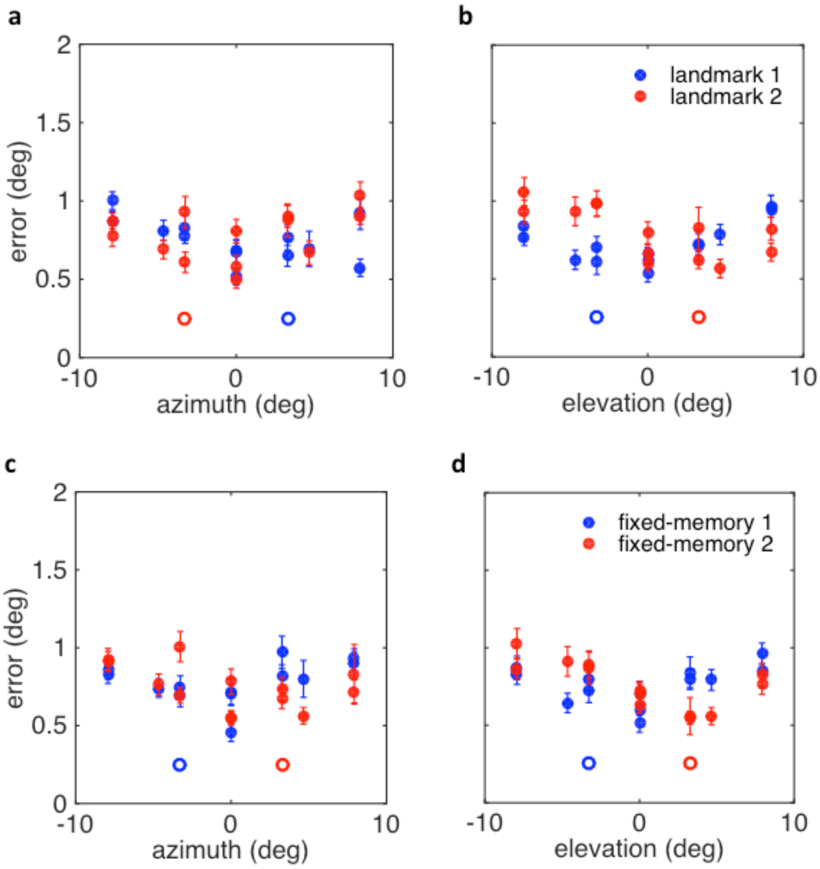

Figure 3.2: *a) The standard deviation of the recall error for the learning session is shown as a function of target azimuth, when the landmark was at location one (shown as blue circle) and two (shown as red circle). b) The recall error as a function of target elevation. c) The standard deviation of the recall error is shown as a function of target azimuth, when the fixed-memory item was at location one (in blue) and two (in red). d) The recall error as a function of target elevation.*

encode and retrieve variable-memory item position. The three groups - morning, afternoon and evening, did not differ significantly in terms of recall precision (for azimuth - F(2,24) = 0.379, p = 0.689; for elevation - F(2,24) = 0.361, p = 0.701) confirming that they learnt and utilised the landmark and fixed-memory item locations similarly.

Figures 3.3a-d also show that targets near the centre of the display, a virtual landmark, were recalled more precisely than those further away from it, as we have shown previously (Katshu & d'Avossa, 2014). ANOVAs showed a significant effect of target position along azimuth (F(11,264) = 6.114, $p < 0.001$) and elevation (F(11,264) = 6.603, $p < 0.001$).

3.4.2 Landmark and fixed-memory item improve recall accuracy during learning

Systematic recall biases reflect the spatial reference frames used to encode spatial information (Katshu & d'Avossa, 2014). To examine whether landmark and/or fixed-memory item affect/s these systematic biases, we measured the recall accuracy of variable-memory item during the learning phase. Figures 3.3a and b show targets in the vicinity of landmark were pushed away from the landmark and towards actual target locations, thereby improving accuracy, compared to targets distant from the landmark. Mixed-model ANOVAs confirmed a significant interaction between landmark and target position (for azimuth - F(11,264) = 3.594, $p < 0.001$; for elevation - F(11,264) = 3.594, $p < 0.001$). Figures 3.3c and d show that fixed-memory item also improved recall accuracy, though to a lesser extent. Mixed-model ANOVAs showed a significant interaction between fixed-memory item and target position along the azimuth (F(11,264) = 2.497, $p = 0.005$) but not along the elevation (F(11,264) = 1.407, $p = 0.170$). Again, the three groups - morning, afternoon and evening, did not differ significantly on recall accuracy (for azimuth - F(2,24) = 0.713, $p = 0.500$; for elevation - F(2,24) = 1.876, $p = 0.175$) confirming that the effects of landmark and fixed-memory item on systematic recall biases were similar across the three groups.

3.4.3 Learnt landmark and fixed-memory item do not affect post-learning recall precision

Do the learnt landmark and fixed-memory item influence spatial recall

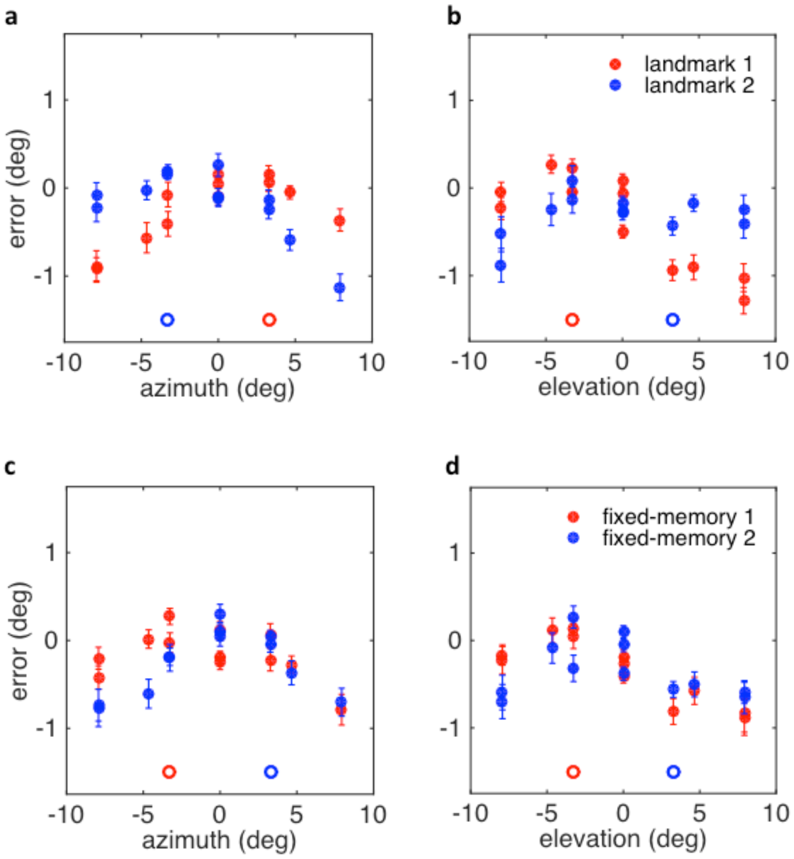

Figure 3.3: *a) The systematic recall bias for the learning session is shown as a function of target azimuth, when the landmark was at location one (shown as red circle) and two (shown as blue circle). (b) The recall error as a function of target elevation. Recalled targets closer to landmarks were systematically displaced outward towards the actual target locations. c) The systematic recall bias is shown as a function of target azimuth, when the fixed-memory item was at location one (shown as red circle) and two (shown as blue circle). d) The recall error as a function of target elevation. Recalled targets closer to fixed-memory item were systematically displaced towards the actual target locations. Negative values reflect displacement towards centre and positive away from centre.*

precision? To ascertain this, we measured variable error in reporting location of a single memory item in pre and post-learning test sessions. Figures 3.4, 3.5 and 3.6 show the standard deviation of variable error of spatial recall in pre and post-learning sessions in the three groups – morning, afternoon and night. Learning the landmark did not affect the spatial recall precision in the post-learning sessions. Mixed-model ANOVAs showed that there was no significant effect of landmark (for azimuth - F(1,24) = 0.125, p = 0.727; for elevation - F(1,24) = 0.005, p = 0.945) nor was there any significant interaction at any level between landmark and target position, session or group. Figures 3.7, 3.8 and 3.9 show that, like landmarks, fixed-memory items also did not have any influence on the recall precision over sessions. Fixed-memory item did not show any effect (for azimuth - F(1,24) < 0.001, p = 0.986; for elevation - F(1,24) = 1.280, p = 0.269) nor was there any significant interaction at any level between fixed-memory item and target position, session or group.

3.4.4 Learnt landmark, but not fixed-memory item, improves post-learning recall accuracy

Do the learnt landmark and/or the fixed-memory item provide reference frames to improve the spatial recall accuracy? We measured the systematic errors in reporting the location of single item in pre and post-learning sessions. Mixed-model ANOVAs showed that there was a significant interaction between target position, landmark, session and group (for azimuth - F(64,768) = 1.876, p < 0.001; for elevation - F(64,768) = 1.802, p < 0.001). Figures 3.10, 3.11 and 3.12 show the effect of landmark on systematic biases in target recall in pre and post-learning sessions in the three groups – morning, afternoon and night. To tease apart these effects further, we computed the difference in systematic bias in reporting targets close to the landmark in landmark centric coordinates between post-learning and pre-learning sessions. Figure 3.13 shows that the eccentric bias with respect to landmark was most prominent in the night group in which learning session was immediately followed by sleep. Follow-up T-tests showed that only post-learning systematic biases in night group reached significant levels (second session – T(22) = 3.627, P = 0.001; third session – T(22) = 2.252, P = 0.034). In contrast, fixed-memory item did not lead to any significant systematic biases in the post-learning sessions. Mixed-model ANOVAs showed no significant interaction between target position, fixed-memory item, session and group (for azimuth - F(64,768) = 0.839, p = 0.809; for elevation - F(64,768) = 0.941, p = 0.608). Nor was there any significant interaction at any level between fixed-memory item, session and sleep. Figures 3.14, 3.15 and 3.16 show the effect of fixed-memory item in pre and post-learning sessions.

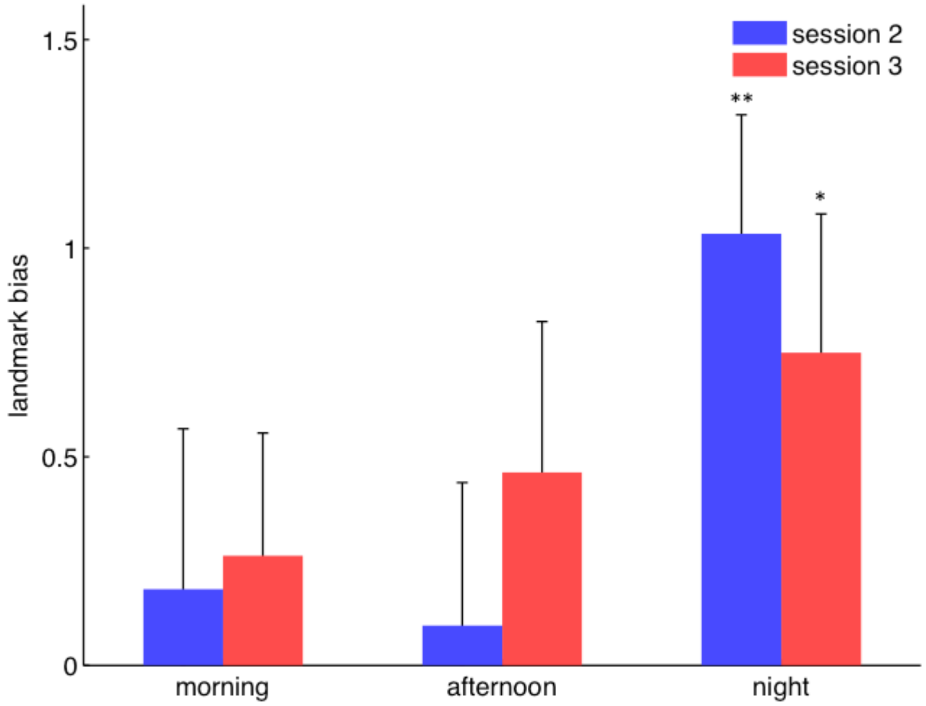

Figure 3.13: *The systematic recall bias difference in landmark centric coordinates between post-learning and pre-learning sessions, difference between session 2 and 1 shown in blue and between session 3 and 1 in red. Eccentric bias with respect to landmark was significant only in the night group in which learning session was immediately followed by sleep.* * *P<0.05, ** P<0.01.*

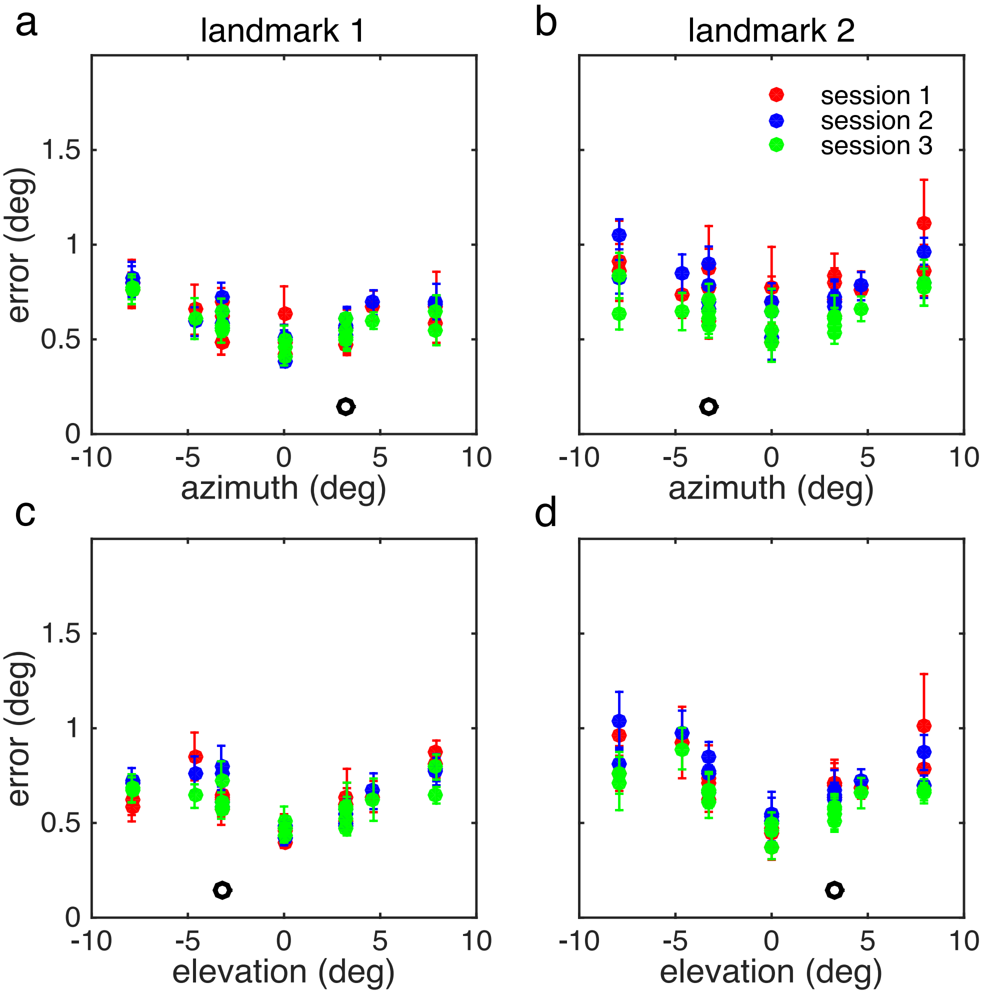

Figure 3.4: *a) The standard deviation of the recall error for test sessions in the morning group is shown as a function of target azimuth when the landmark, whose location is shown as a black circle, was at location one and b) two. c) The recall error as a function of target elevation when landmark was at location one and d) two. There was no significant difference in recall errors across sessions.*

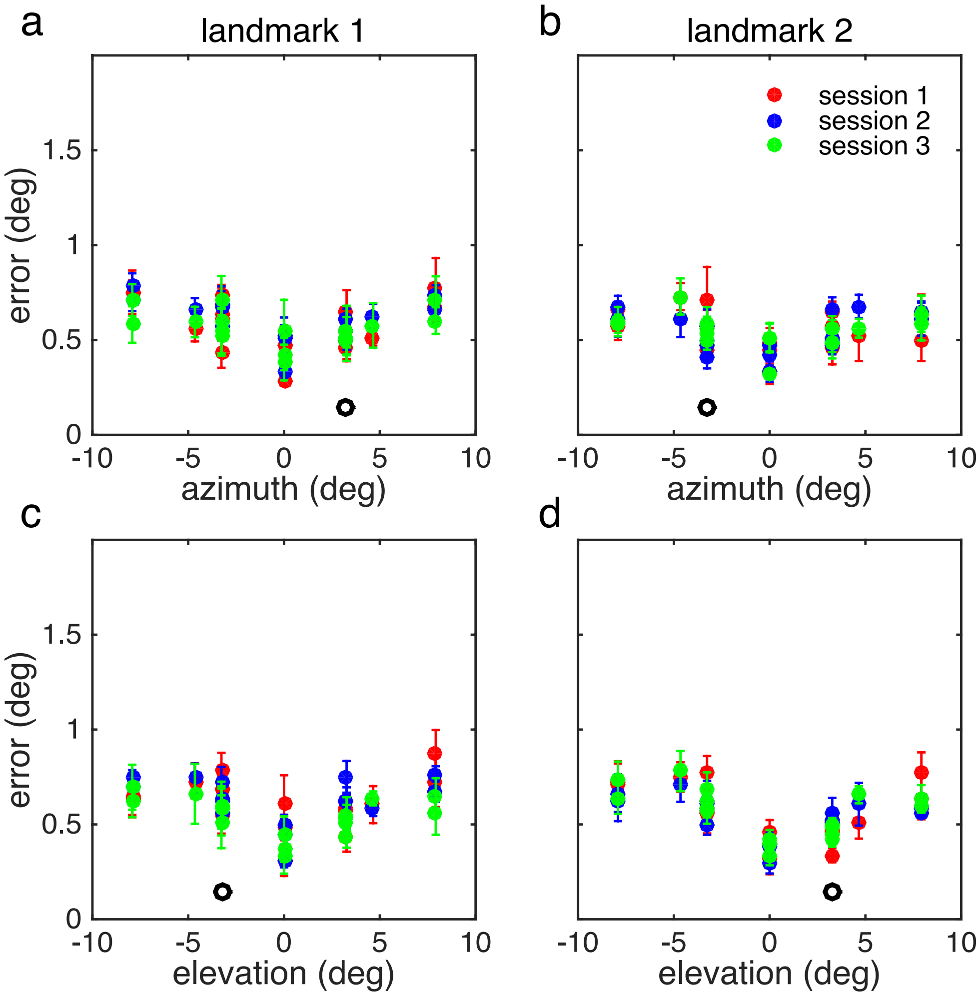

__Figure 3.5:__ a) The standard deviation of the recall error for test sessions in the afternoon group is shown as a function of target azimuth when the landmark, whose location is shown as a black circle, was at location one and b) two. c) The recall error as a function of target elevation when landmark was at location one and d) two. There was no significant difference in recall errors across sessions.

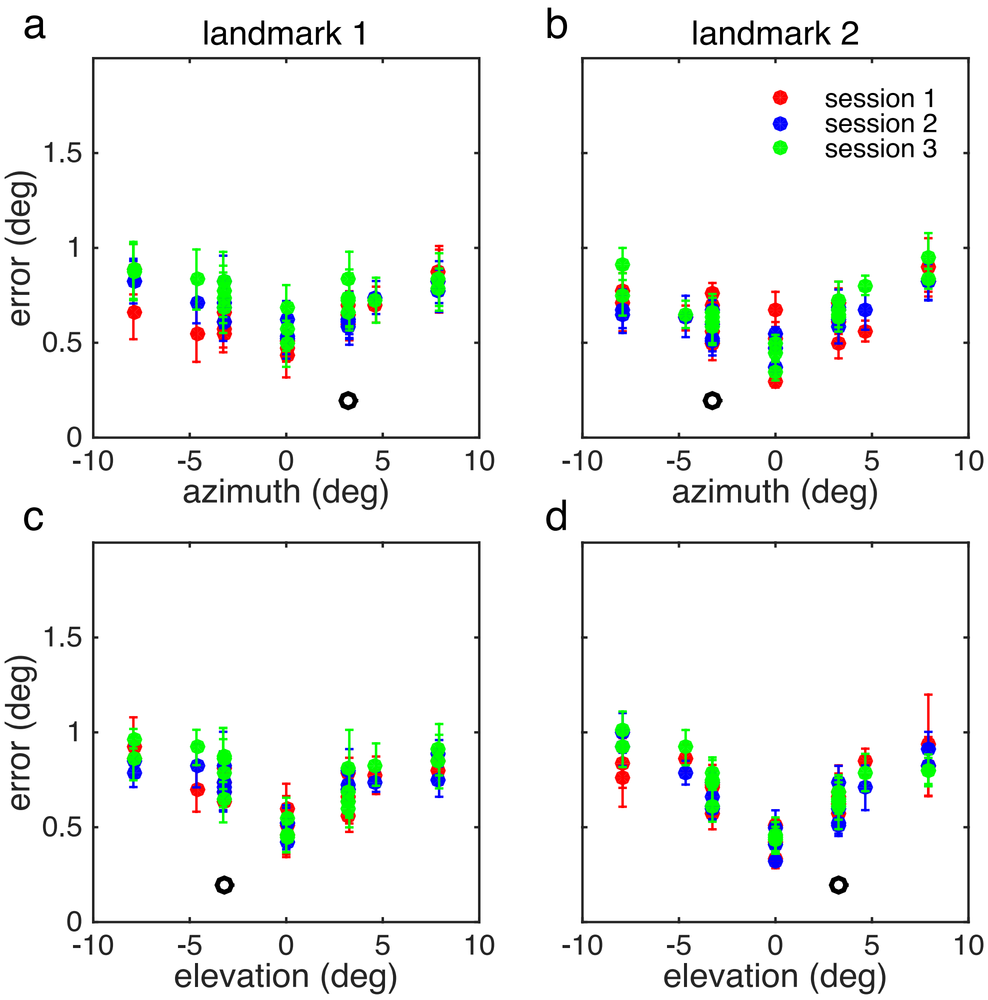

Figure 3.6: *a) The standard deviation of the recall error for test sessions in the night group is shown as a function of target azimuth when the landmark, whose location is shown as a black circle, was at location one and b) two. c) The recall error as a function of target elevation when landmark was at location one and d) two. There was no significant difference in recall errors across sessions.*

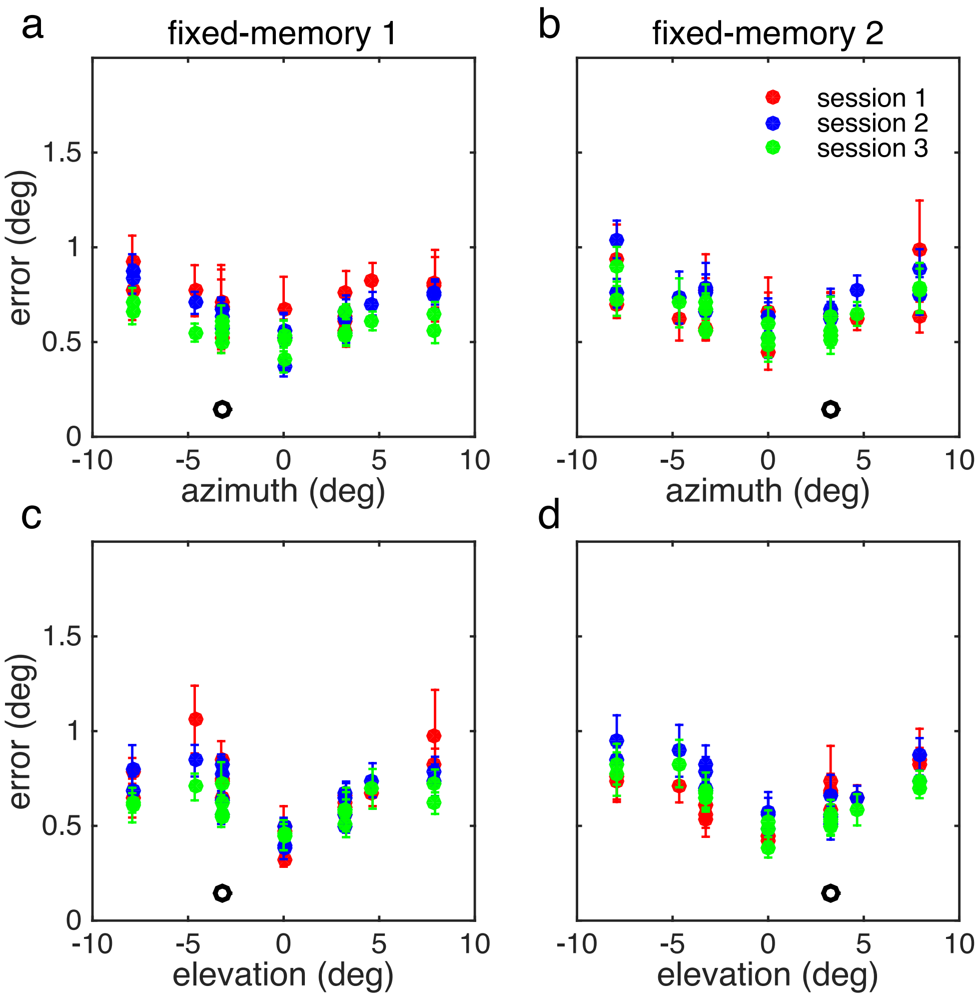

Figure 3.7: *a) The standard deviation of the recall error for test sessions in the morning group is shown as a function of target azimuth when the fixed-memory item, whose location is shown as a black circle, was at location one and b) two. c) The recall error as a function of target elevation when the fixed-memory item was at location one and d) two. There was no significant difference in recall errors across sessions.*

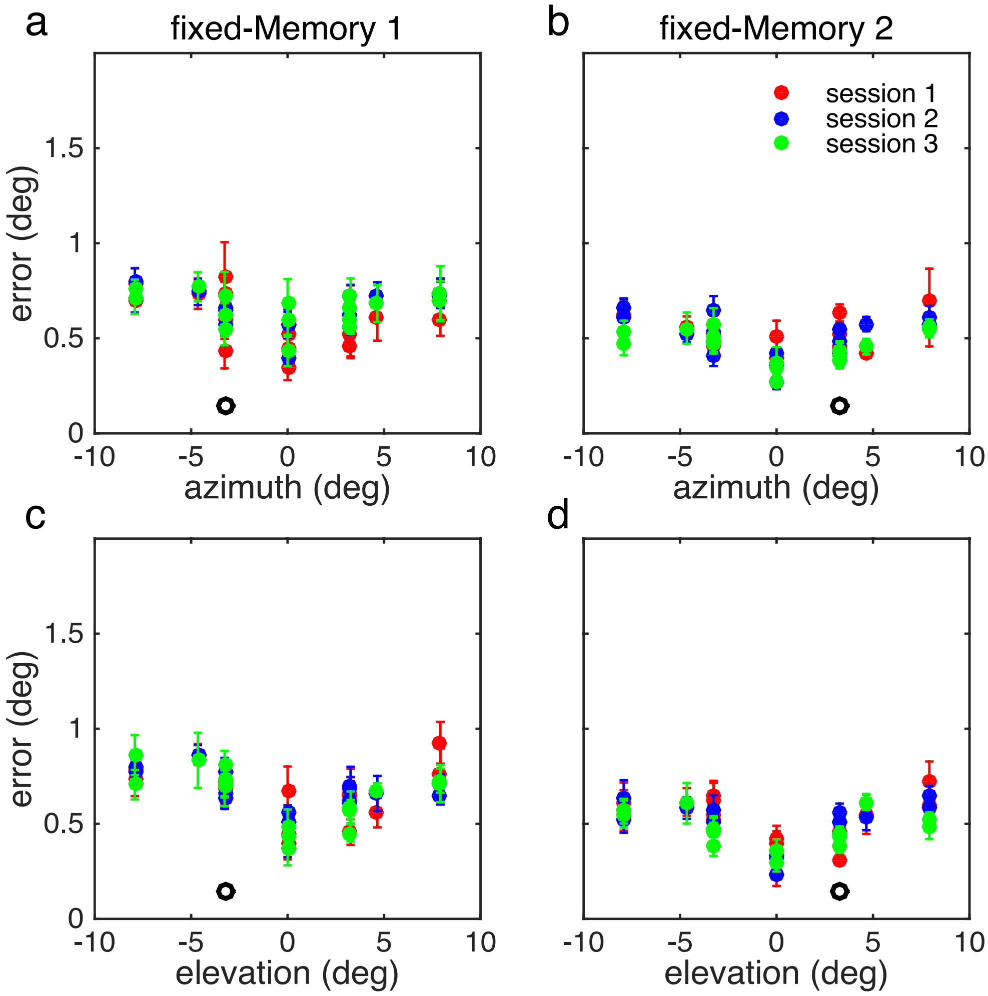

Figure 3.8: *a) The standard deviation of the recall error for test sessions in the afternoon group is shown as a function of target azimuth when the fixed-memory item, whose location is shown as a black circle, was at location one and b) two. c) The recall error as a function of target elevation when the fixed-memory item was at location one and d) two. There was no significant difference in recall errors across sessions.*

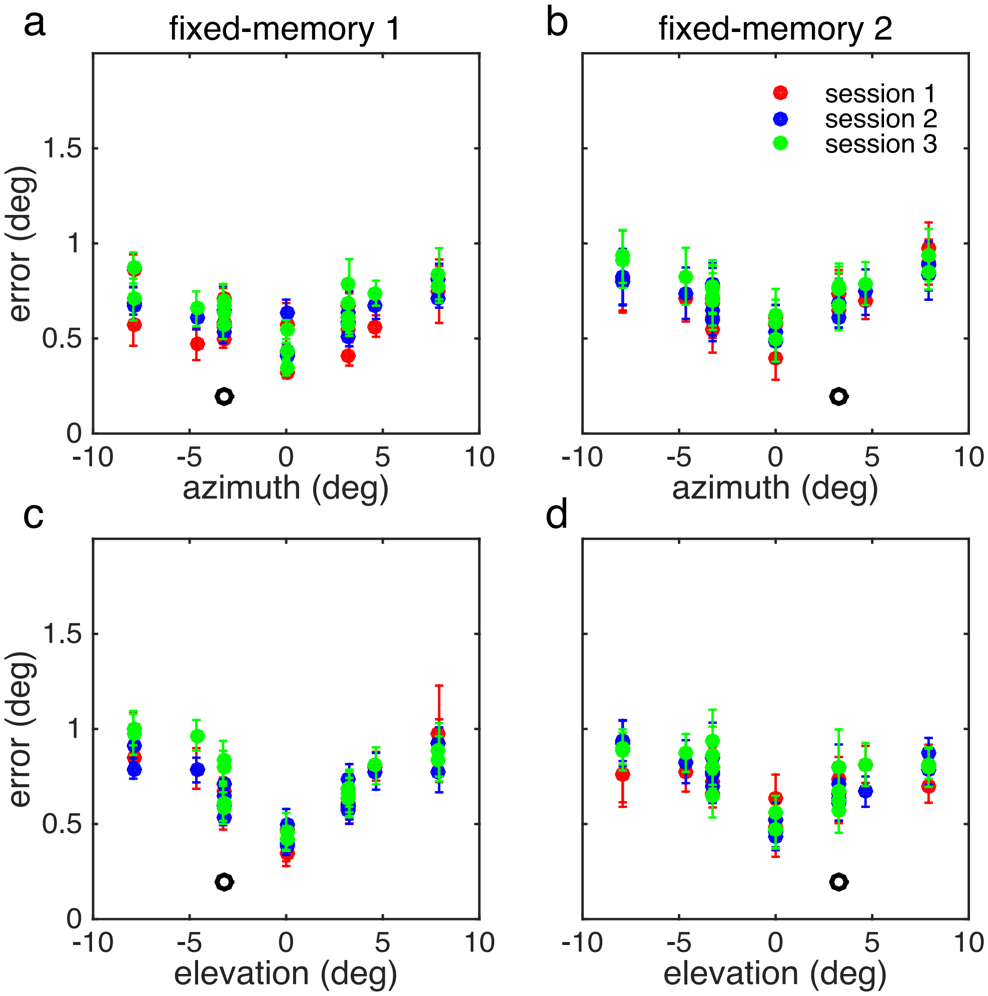

__Figure 3.9:__ a) The standard deviation of the recall error for test sessions in the night group is shown as a function of target azimuth when the fixed-memory item, whose location is shown as a black circle, was at location one and b) two. c) The recall error as a function of target elevation when he fixed-memory item was at location one and d) two. There was no significant difference in recall errors across sessions.

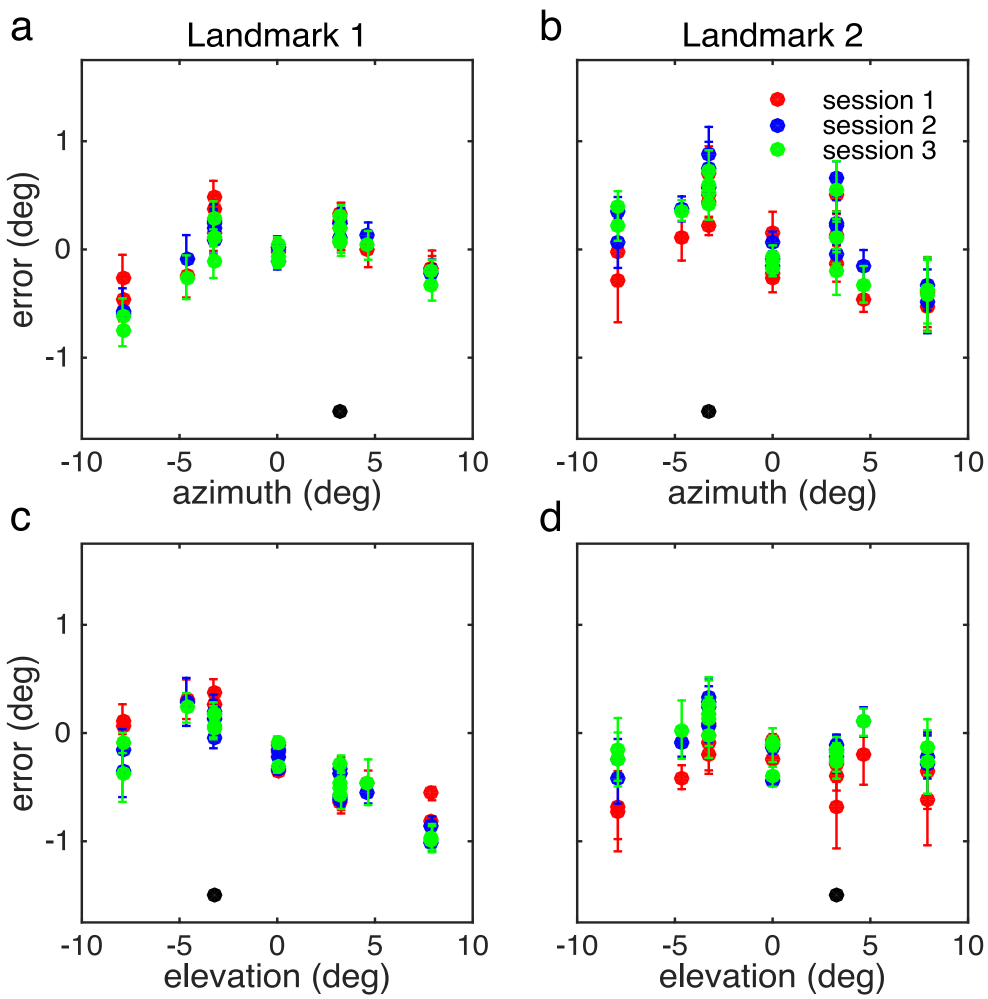

Figure 3.10: *a) The systematic recall bias for test sessions in the morning group is shown as a function of target azimuth when the landmark, whose location is shown as a black dot, was at location one and b) two. (c) The recall bias as a function of target elevation when landmark was at location one and d) two. Negative values reflect displacement towards centre and positive away from centre. There was no significant difference in recall bias across sessions.*

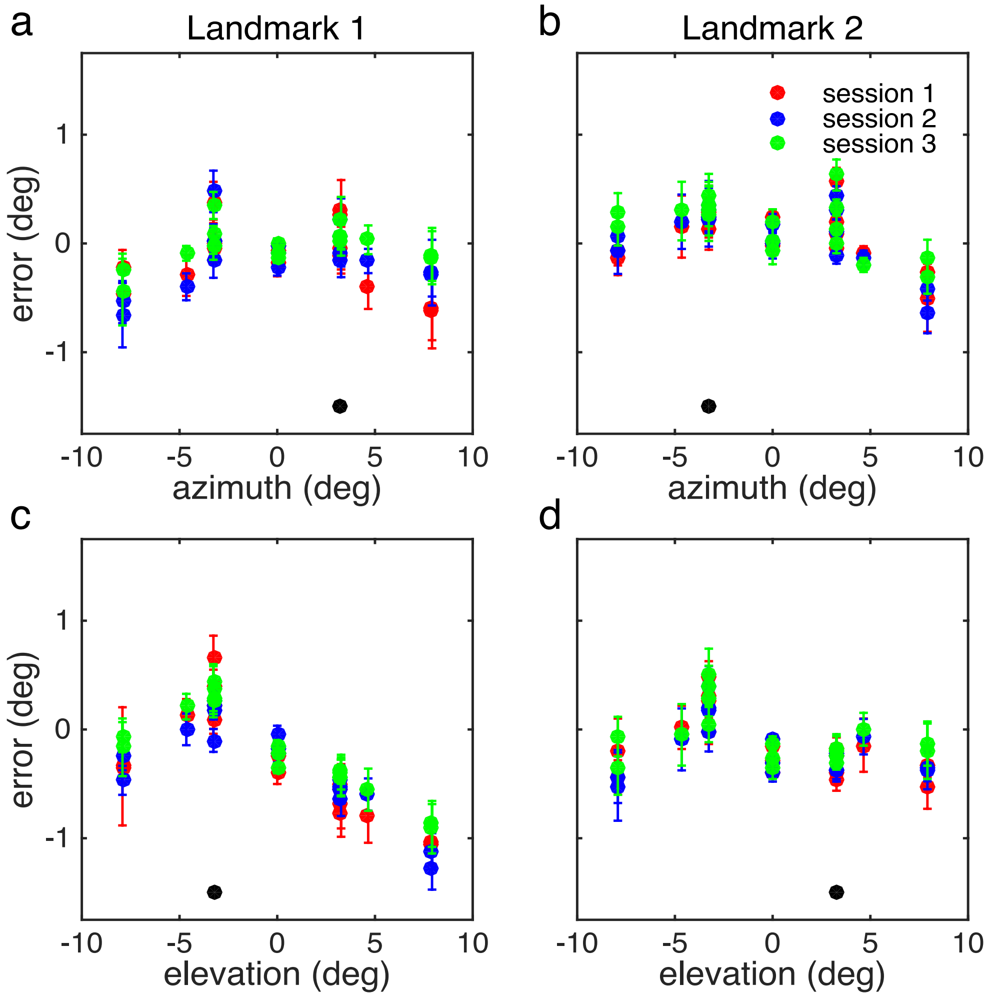

Figure 3.11: *a) The systematic recall bias for test sessions in the afternoon group is shown as a function of target azimuth when the landmark, whose location is shown as a black dot, was at location one and b) two. c) The recall bias as a function of target elevation when landmark was at location one and d) two. Negative values reflect displacement towards centre and positive away from centre. There was no significant difference in recall bias across sessions.*

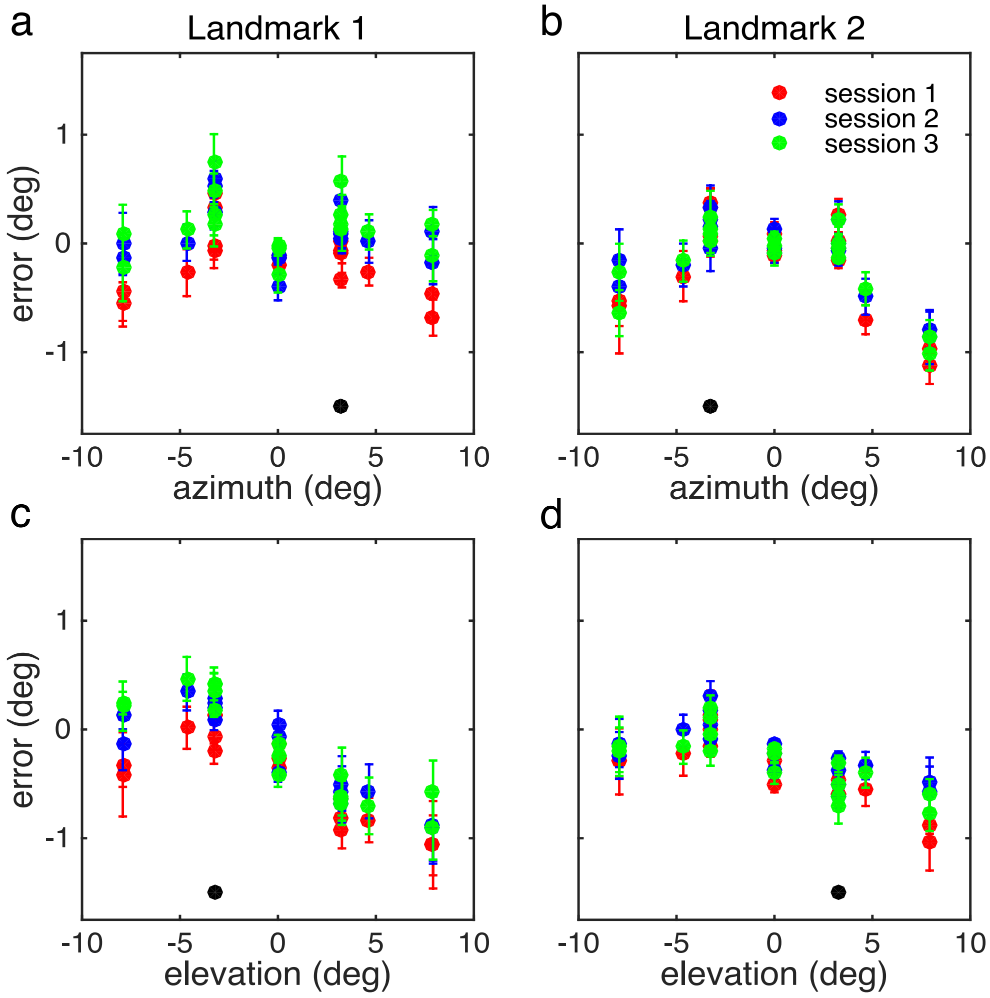

Figure 3.12: *a) The systematic recall bias for test sessions in the night group is shown as a function of target azimuth when the landmark, whose location is shown as a black dot, was at location one and b) two. c) The recall bias as a function of target elevation when landmark was at location one and d) two. Negative values reflect displacement towards centre and positive away from centre. There was a significant difference in recall bias at target positions near landmarks across sessions, specifically targets closer to landmarks showed significant landmark centred biases in the second and third session.*

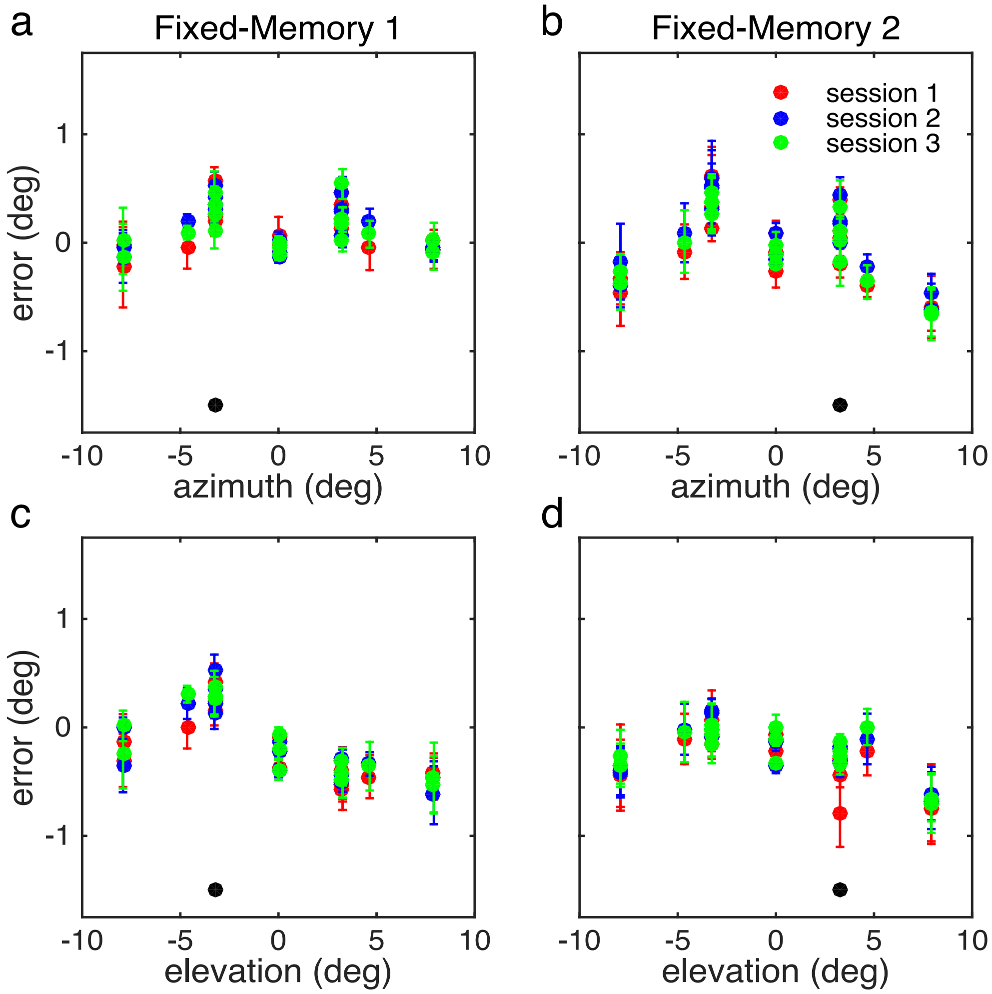

Figure 3.14: *a) The systematic recall bias for test sessions in the morning group is shown as a function of target azimuth when the fixed-memory item, whose location is shown as a black dot, was at location one and b) two. c) The recall bias as a function of target elevation when the fixed-memory item was at location one and d) two. Negative values reflect displacement towards centre and positive away from centre. There was no significant difference in recall biases across sessions.*

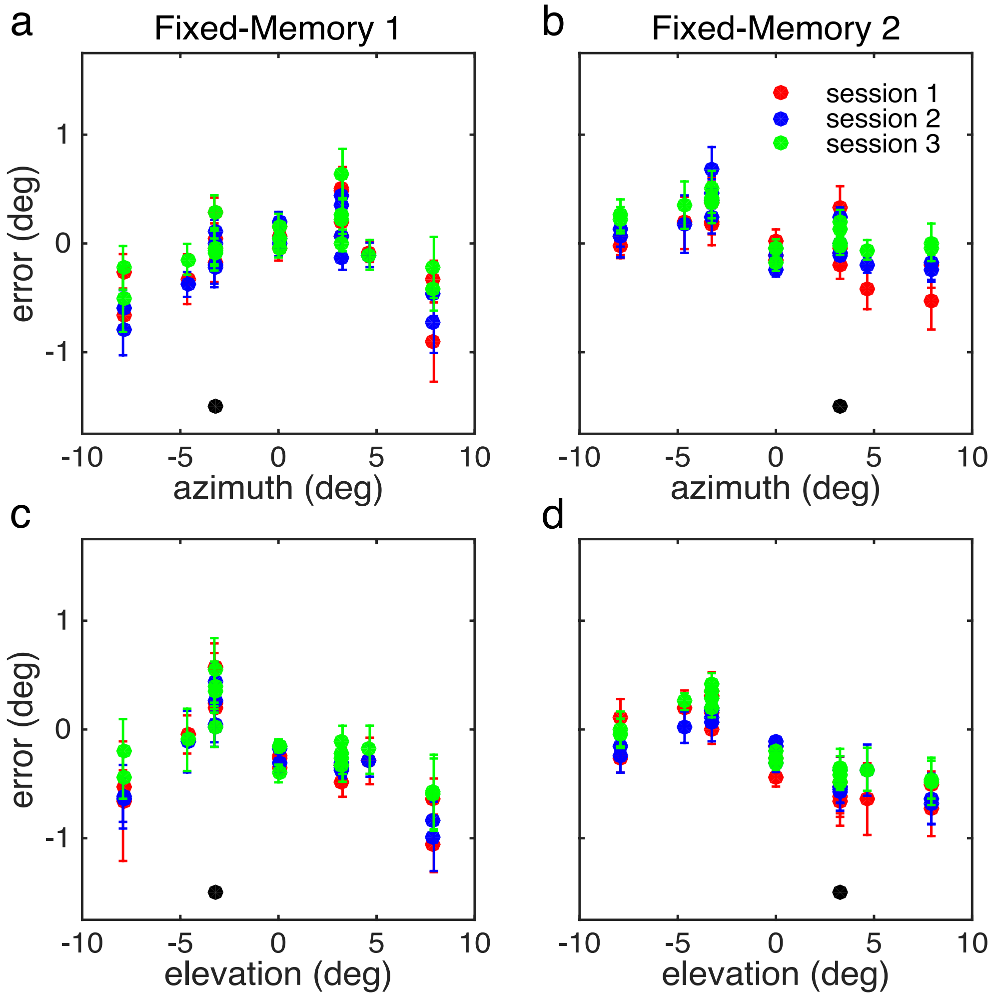

Figure 3.15: *a) The systematic recall bias for test sessions in the afternoon group is shown as a function of target azimuth when the fixed-memory item, whose location is shown as a black dot, was at location one and b) two. c) The recall bias as a function of target elevation when the fixed-memory item was at location one and d) two. Negative values reflect displacement towards centre and positive away from centre. There was no significant difference in recall biases across sessions.*

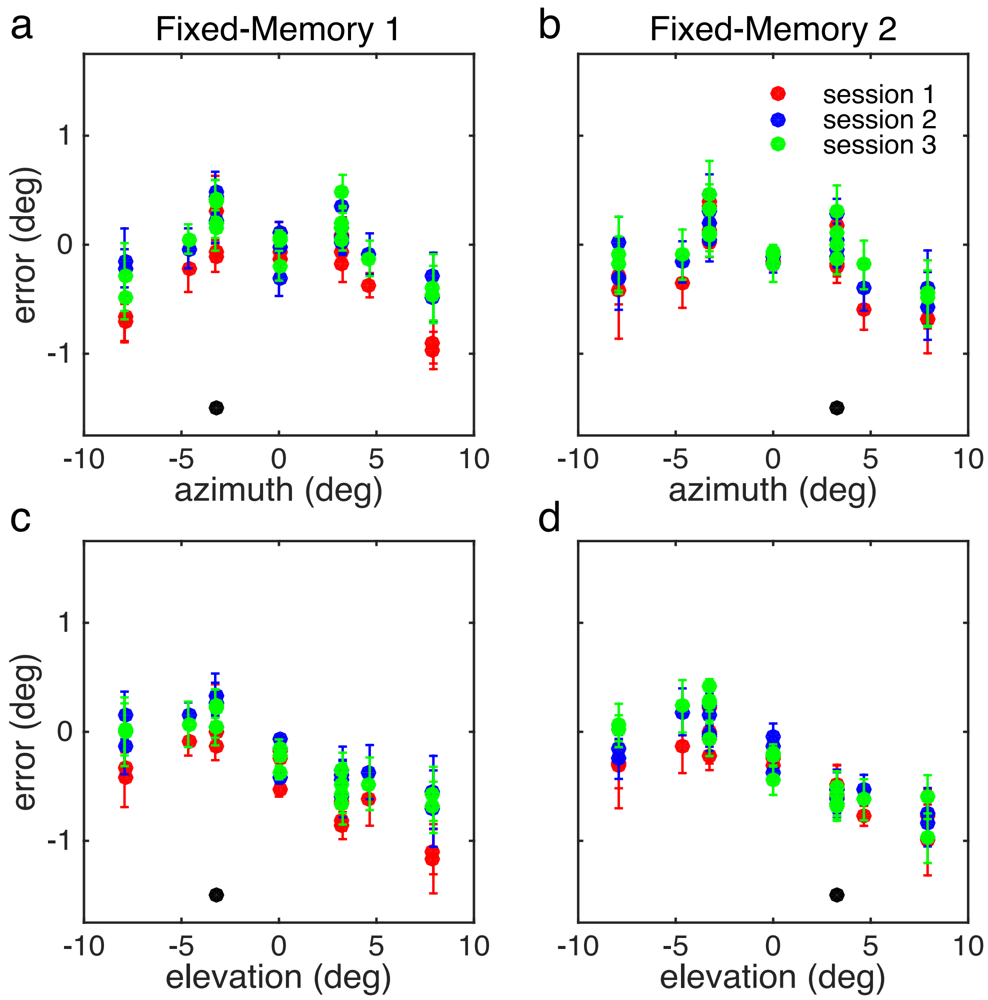

Figure 3.16: *a) The systematic recall bias for test sessions in the night group is shown as a function of target azimuth when the fixed-memory item, whose location is shown as a black dot, was at location one and b) two. c) The recall bias as a function of target elevation when he fixed-memory item was at location one and d) two. Negative values reflect displacement towards centre and positive away from centre. There was no significant difference in recall errors across sessions.*

3.5 Discussion

In this study, we examined the effects of naturalistic sleep on the consolidation of intentionally and incidentally memorised visual data. The experimental design included an initial learning block, in which participants had to recall, after a short delay, the location of one of two coloured discs. One of the discs appeared at the same position in every trial, the other's position varied from trial to trial. In both the sample and recall displays, a visually distinct landmark was shown, which did not provide any information about the memory target's position. The landmark always appeared at the same position. The participants completed one pre-learning and two post-learning blocks, spaced 8 hours apart. In these blocks, participants memorised and recalled the position of a single visual item. The landmark was shown in the recall, but not the sample display. In the learning block, clear changes in spatial recall precision and accuracy for targets close to either the landmark or the fixed-memory location were found, suggesting configurational effects in memory encoding and recall.

We found that in the post-learning blocks, recall accuracy and precision for targets at the location, which had been occupied by the fixed-memory item, was no better than for targets appearing at other locations. However, the accuracy of spatial recall was higher for items appearing closer to the landmark than for items appearing further away. This effect was greatest when the participants had the opportunity to sleep immediately after the learning block. These findings suggest that the spatial distribution of the memory items did not have a sustained effect on spatial recall, but that the location of the landmark did. More importantly, these results have implications for the nature of the interactions between spatial LTM and WM and for the role of sleep in spatial memory. We will discuss these in greater detail next.

3.5.1 Learnt landmarks improve recall from sWM

Limited WM capacity poses significant constraints on task performance. A number of strategies may be available to circumvent these limitations. A well-known proposal is that encoding of novel information into WM can be improved by exploiting regularities, stored in LTM. For example, the string ‘W’, ‘A’ and ‘R’ can be either encoded as three separate characters or as a single martial noun. Chunking the string into a single word is deemed to minimise the memory load, thus increasing the apparent capacity of WM (Ericsson & Kintsch, 1995; Gobet et al., 2001). A related proposal is that visual WM holds both chunked representations of a scene’s overall configuration as well as the individual items therein (Brady & Alvarez, 2011). The former may provide a rough estimate of an individual items’ feature value in the face of item level uncertainty at the time of recall. Knowledge of the probability distribution of features values in familiar scenes may not only aid their recall, but also their efficient encoding in vWM (Brady & Oliva, 2008). Finally, when observers search for a target, they may incidentally encode the search array into memory, facilitating subsequent searches, when the same scene is repeatedly presented (Woodman & Chun, 2006). Theoretical proposals have generally emphasised the fact that contextual information, namely regularities in familiar visual scenes, provides ample opportunities for improving the encoding and recall of visual data.

Authors of the classical period, who described the method of loci to improve recall, viewed limitations of human memory differently. They suggested that recall is limited by inefficient search of memory registers. By placing memorised information in the halls and rooms of memory palaces, which are highly rehearsed imaginary buildings, a trained mnemonist could quickly learn to systematically address and retrieve large amounts of stored information (Cicero, 1954; Yates, 1992). This proposal does not require a mapping between the statistics of the encoded stimulus and the structure of the memory palace. On the contrary, chunking and other recent context based suggestions require that stored information matches stored templates based on familiar configurations.

The findings suggest that spatial recall from WM in the post-learning phase was affected by learning the position of the landmark. First, targets close to the landmark were recalled displaced away from the landmark position in post-learning blocks, similarly to what was observed in this and previous studies when the landmark persists throughout the sample and recall display. Moreover, this effect was not simply perceptual due to the presence of a visible landmark in the recall display, since it was greatly diminished when participants had not had a chance to sleep. These findings suggest that only after the landmark is consolidated in LTM, the landmark can be used to facilitate the encoding of the target position in WM and facilitate its later recall. Notably, the landmark did not predict the location of the target and, therefore, its effects on encoding and recall could not reflect the exploitation of a statistical regularity in the relation between the target and landmark positions. Rather, this finding indicates that landmark provides a scaffold for the construction of internal maps in LTM, which improve the ability to encode and recall spatial data in WM. These accounts are supported by recent evidence showing improved digit span performance by improving recall through learnt spatial information in LTM, known as visuo-spatial bootstrapping (Darling et al., 2014). On the other hand, having found no difference in the recall of targets at overlearnt compared to other locations, we conclude that the spatial distribution of memorised items does not affect in a sustained manner the encoding and retrieval of spatial information from WM. Therefore, the idea that the probability distribution of memorised data shapes its encoding does not extend to the encoding for spatial data in our experiment.

We measured the spatial recall of a single target in the pre and post-learning sessions and so it is possible that the demands on WM were low or sub-span and did not recruit the LTM, thereby explaining no change in spatial recall precision. This may hold true for WM tasks based on categorical judgments like change detection where participants' performance is near ceiling for 3-4 items, however our task involved precise recall of spatial information and participants showed significant recall errors. Also, learnt landmarks improved spatial recall of targets in their vicinity, thereby confirming that participants' performance was not at ceiling.

3.5.2 Sleep consolidates the landmark effects on sWM

Sleep is known to promote memory consolidation, its effects generalising to both declarative and procedural aspects (Diekelmann & Born, 2010). Effects of sleep on performance of low-level visual tasks, where retinotopically specific improvements are observed have also been described, suggesting that sleep can interact with focal changes in neural circuitry (Mednick et al., 2002; Mednick, Nakayama, & Stickgold, 2003). Our findings add to that evidence by indicating that sleep helps consolidate changes in long-term spatial memory associated with incidental encoding of landmark positions. Spatial learning is associated with specific patterns of activation of hippocampal cell assemblies. Reactivation of these patterns during sleep is believed to consolidate memories of spatial layouts (Fuentemilla et al., 2013; Ji & Wilson, 2007; Peigneux et al., 2004; Wilson & McNaughton, 1994). Post-learning sleep has also been shown to improve spatial WM accuracy, which has been suggested to reflect an improvement in sWM capacity (Kuriyama et al., 2008). However, the modified n-back task used in this study involved high executive demands and procedural learning and the study's design could not distinguish whether performance changes following training were due to a material specific increase in WM capacity or rather a material general, but process specific improvement (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). In contrast, our task was simple, had minimal executive demands and procedural learning requirements, thereby reflecting more direct assessment of storage capacity. We found that post-learning sleep lead to sustained, landmark-centred changes in spatial recall accuracy, but it did not improve the overall accuracy or precision of recall.

Moreover, sleep had the greatest effect when it followed the learning phase, rather than when it was delayed. We conclude that sleep does not improve the overall capacity of sWM, but rather it consolidates incidental landmarks and that sustained plastic changes are consolidated in a time critical manner.

3.5.3 sWM is supported by multiple, local and global, representations

The two predominant contemporary models of WM, fixed-slots and flexible-resource, are based on the assumption that features of different items are stored independently of each other (Bays & Husain, 2008; Zhang & Luck, 2008). These models not only fail to account for the effect of same dimension features of other items in the display on recall, but also leave no room for mechanisms, probabilistic or referential, through which LTM improves sWM recall. An alternative proposal put forth recently conceptualises sWM as supported by multiple level representations including local, high fidelity spatial maps and coarse representations of the overall configuration (Katshu & d'Avossa, 2014). This model proposes sWM recall to be a function of individual target's variable resolution representation, determining recall precision, as well as influenced by the overall configuration of the targets in the display, determining recall accuracy. Recent neurophysiological evidence is consistent with the multiple representation model of WM. BOLD signal patterns in early Visual cortex during maintenance phase of WM convey information about memorised targets, while neuronal activity in Parietal cortex of primates reflects the spatial configuration of the memory array (Emrich et al., 2013; Harrison & Tong, 2009; Riggall & Postle, 2012; Serences et al., 2009). This model allows for the improved sWM recall accuracy but not precision through learnt landmarks observed in this study. Targets in the display can be referenced to learnt landmarks and the resulting configurational representations improve recall accuracy.

Chapter 4: Medial Occipito-Temporal Cortical lesions affect binding of spatial and non-spatial information and temporal decay in working memory

4.1: Abstract

Lesions of medial Occipito-Temporal cortex (mOTC) result in acute impairments of attention and working memory (WM), and sustained spatial disorientation. We examined a 46-year-old man, who had suffered bilateral mOTC strokes. When recalling the colour of one of two objects, he frequently misidentified the target when cued by its location, but not shape. When recalling the position of one of three coloured objects cued by colour, he also misidentified the target. These errors were as frequent following short and long delays. On the other hand, when localizing the centroid of three-dot displays, and recalling the position of one of three objects cued by colour after a 1.0s delay, his precision was comparable to controls. However, while recalling the position of one of three objects cued by colour his precision after a 5.0s delay was disproportionately diminished. We conclude that mOTC is involved in two processes: 1) binding of spatial and non-spatial information in WM, and 2) maintaining the spatial resolution of memorised data in the face of temporal decay. mOTC may, therefore, provide the spatial scaffold required for basic cognitive operations.

4.2 Introduction

Dense anterograde amnesia follows lesions along the medial Temporal lobe (MTL), which includes the Hippocampus, Entorhinal and Perirhinal cortex and Parahippocampal Cortex (PHC), suggesting that these structures play a prominent role in maintenance and recall of episodic memories (Corkin et al., 1997; Corkin, Kosslyn, & Andersen, 1992; Scoville & Milner, 1957). However, this view does not clearly account for the acute impairments of perception and working memory (WM) that follow ischemic lesions ventral and posterior to the Hippocampus (Horenstein, Chamberlain, & Conomy, 1967; Medina, Chokroverty, & Rubino, 1977; Schmidley & Messing, 1984; Shih et al., 2007). It has been suggested that PHC and the Hippocampus have a modular organization, with each area playing a specific and distinct role in either encoding, recalling or recognizing (Eichenbaum, Yonelinas, & Ranganath, 2007; Eichenbaum, Sauvage, Fortin, Komorowski, & Lipton, 2012). This proposal provides the theoretical underpinnings for the view that the medial Occipito-Temporal cortex (mOTC) may play a role in processes beyond episodic memory (Murray, Bussey, & Saksida, 2007; Suzuki, 1996), although defining the core functionality of each area has proven difficult.

For example, imaging studies in healthy participants have demonstrated that learning and recall of spatial layouts (Epstein, Harris, Stanley, & Kanwisher, 1999; Epstein & Kanwisher, 1998; O'Craven & Kanwisher, 2000; Staresina, Duncan, & Davachi, 2011) and passive viewing of images of buildings, outdoor scenes and natural landscapes (Epstein et al., 1999) activate PHC, which comprises the portion of mOTC posterior to the Hippocampus. These findings have suggested that parts of mOTC may support navigation (Epstein, 2008) by enabling the recognition of distinctive landmarks, a proposal consistent with the observation that patients with PHC lesions can develop difficulties negotiating both familiar and unfamiliar environments following mOTC strokes (Aguirre, Detre, Alsop, & D'Esposito, 1996; Epstein, Deyoe, Press, Rosen, & Kanwisher, 2001; Habib & Sirigu, 1987). However, other imaging results have shown selectivities, which are not obviously consistent with this specific view of the function of PHC. For example, PHC shows modulation of functional signals by the contextual value of objects and scenes, suggesting that it may maintain a repertoire of familiar places and non-spatial attributes that facilitate the encoding of events in memory and their recall (Aminoff, Kveraga, & Bar, 2013; Bar & Aminoff, 2003). These observations are in keeping with the proposed role of PHC in providing the spatial context for episodes stored in memory (Eichenbaum et al., 2007). Others have suggested that the Occipito-Temporal cortex (OTC) is functionally parcellated; while mOTC encodes large objects, lateral OTC encodes small objects, a conclusion that may be consistent with a role of the former in the recognition of large, visual landmarks (Konkle & Oliva, 2012; Troiani, Stigliani, Smith, & Epstein, 2014). However, it remains unclear why, following acute ischemic damage to the mOTC, impaired encoding of contextual and/or landmark information should produce perceptual and WM memory impairments.

Studies in non-human primates found that lesions in regions surrounding the Hippocampus hamper novelty recognition and location recall (Winters, Forwood, Cowell, Saksida, & Bussey, 2004), even after delays of only few seconds. Monkeys with PHC lesions cannot retrieve a morsel of food when having to reach for either a location previously highlighted, or from unique conjunction of marker and location (Bachevalier & Nemanic, 2008; Malkova & Mishkin, 2003). These findings suggest that PHC may play a broad role in handling spatial data, including locations in the close peri-personal space. Since patients with PHC lesions also exhibit delay-dependent decrements in spatial recall from WM (Ploner et al., 2000), there may be significant cross-species homologies in the functionality of this region.

Animal studies indicate that PHC is part of a broader circuit. It projects to medial Entorhinal cortex, where units with periodic spatial receptive fields provide the main input for the computation of the organism's position that is carried out in the Hippocampus (e.g. Moser, Kropff, & Moser, 2008). On the other hand, object-related information is summarized in Perirhinal cortex, which provides the main input to lateral Entorhinal cortex and then Hippocampus (Suzuki, 1996). This anatomical organization suggests that there is a separation between spatial and object streams in ventral OTC. Information from these two streams is eventually bound in the Hippocampus (Diana, Yonelinas, & Ranganath, 2007; Eichenbaum et al., 2007). In keeping with this idea, studies on non-human primates have demonstrated that lesions in PHC, Perirhinal cortex and Hippocampus all lead to difficulties forming associations between objects and their location (Bachevalier & Nemanic, 2008).

Given the clinical and lesion evidence, we assumed that mOTC must support basic spatial processes, which include memory as well as perceptual functions. We tested a man with bilateral posterior cerebral artery strokes involving the mOTC, but sparing the Hippocampus, Perirhinal cortex and with limited encroachment on regions lateral to the collateral sulcus. The patient showed impaired binding of location and colour of simple objects, while showing no impairment in binding colour and shape on recall after brief delays. The binding impairment was not modulated by the duration of the delay period. Also, the precision of spatial recall over brief delays was comparable to controls, even though longer memory delay disproportionally worsened the precision of spatial recall. Moreover, there was no impairment in localizing the centroid of three-dot displays. Therefore, mOTC subserves at least two separate functions: binding visual information to its location in WM, and maintaining the resolution of spatial data in WM.

4.3 Methods

4.3.1 Participants

The patient was initially assessed by one of the authors during the provision of outpatient clinical care. Later, he was approached and offered the possibility to take part in research activities. The patient was 45 years old at the time of the presenting event. He developed headaches, and visual and mental status changes over the course of few hours. Two days after the onset of the symptoms, he was admitted to a stroke-unit. During the admission, he continued to be confused and agitated. The diagnostic work-up did not identify the cause of the stroke. The patient had no significant medical history except for cluster headaches, which responded to standard treatment. Upon returning home, the patient was not able to resume his full-time occupation as an animal breeder because of difficulties finding his way around the house and farm, where he had moved two years prior. He also relinquished driving because he could not find his way around familiar streets. He also had difficulty recognizing the different rooms of his residence despite being able to draw a layout plan of the house as good as his wife. The family had resorted to placing signs on the internal doors to help him identify different rooms. His ability to locate tools in his farm was also diminished. Four months after the event, a clinical assessment revealed on-going difficulties with WM, bilateral upper visual field loss and fatigue. Formal psychometric testing revealed that his general intellectual function was in the normal range, as measured with the Wechsler Adult Intelligence scale, IV edition (Wechsler, 2008). There was no significant difference between his performance on the verbal (Verbal Comprehension Index) and non-verbal scale (Perceptual Reasoning Index). Language function was generally intact, including comprehension and expressive abilities. While basic attention was intact, he clearly had difficulty holding and manipulating information in his mind, reflecting a WM deficit. Overall visual and perceptual functioning appeared to be within normal limits, though he showed difficulties with visual scanning, most likely due to his visual field deficits. Memory function was significantly impaired for both visual and verbal material and to a similar extent. He had difficulties with learning/acquisition of new material and with delayed recall. Performance was not improved for recognition memory, suggesting an underlying amnestic syndrome. Performance on executive functioning tasks was mixed; he performed below expectations on a planning and problem-solving task and also with a visual set-shifting task. His performance on a verbal fluency task was also lower than expected. His performance on these tasks may have been affected by his underlying memory and visual deficits (Table 1).

Table 1: Patient's neuropsychological assessment

Wechsler adult Intelligence Scale (WAIS) IV			
Test	**Scaled score**	**Test**	**Scaled score**
Vocabulary	9	Visual puzzles	11
Similarities	9	Digit-symbol coding	5
Arithmetic	8	Block design	9
Forward digit span	9	Matrix reasoning	5
Backward digit span	7	Symbol search	7
Information	10		
Verbal comprehension index	96	Perceptual reasoning index	90
Working memory index	92	Processing speed index	79
Full-scale IQ	87		

Wechsler Memory Scale III		
Test	**Raw score**	**Scaled score**
Logical memory I	11/75	2
Logical memory II	4/50	3

Logical memory II recognition	13/30	
Logical memory I (thematic)	6/23	3
Logical memory II (thematic)	5/15	5
Delis–Kaplan Executive Function System Verbal Fluency test		
Test	**Total score**	**Scaled score**
Letter fluency	25	6
Category fluency	39	10
Benton Visual retention test		
Number of correct designs	Number of errors	
3	13	
Trail making test		
Test	**Time (sec)**	**Percentile**
Part A	72	<1
Part B	131	<1
Rey Auditory Verbal Learning Test – List A		
Trial	**Total**	**Percentile**
I	3	2
II	4	1
III	5	2
IV	8	13
V	5	<1
List B	4	13
VI	3	2
Delay	1	1
Recognition	1	<1

Rey-Osterrieth Complex Figure Test

Trial	Total	Percentile
Copy	36	92
Recall (30 mins)	1.5	1

Tower of Hanoi

	1	2	3	4	5	6
3/6	9	6	6			
3/7	7	7				
4/7	9	7	7			
4/11	21	11	11			
4/15	26	16	25	DC	15	15

Ten male, right-handed, neurologically healthy control participants were recruited via Bangor University and the local community. Controls were screened for any history of major neuropsychiatric disorders and visual impairments (Appendix 1). Table 2 summarises the participant characteristics of the control group; controls had a mean age of 48.2 years (s. d. = 6.4), mean IQ of 101.1 (s. d. = 7.6) and a mean age at leaving school of 16.6 years (s. d. = 0.7). IQ was measured with the 2-subtest (vocabulary and matrix reasoning) version of the Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999). Participants and the patient were compensated for their time and travel expenses. All participants gave written, informed consent prior to initiating any experimental procedure. The testing procedures were reviewed and approved by the Betsi Cadwaladr University Health Board and the Bangor University, School Psychology Ethics committees.

Table 2: Control participants' demographic characteristics

	Age	IQ	School leaving age
	51	106	18
	43	111	16
	45	99	16
	61	103	17
	39	109	18
	47	90	16
	53	88	16
	46	104	17
	53	97	16
	44	104	16
Mean	48.2	101.1	16.6
SD	6.4	7.6	0.8

4.3.2 Structural Imaging

The patient was scanned on a Phillips Achieva 3T MR scanner housed in the School of Psychology, Bangor University. Two T1-weighted images and a FLAIR image were acquired with 1.0mm isotropic voxel-size. The T1-weighted images were realigned and averaged. The data were then transformed into Talairach space, using a twelve-degrees of freedom affine transformation to an atlas representative target image. The lesion boundaries were segmented manually under the supervision of a board certified adult neurologist, using the co-registered T1 and FLAIR images, with Analyse (AnalyzeDirect, Overland Park, KS, USA). Figure 4.1 shows the extent of lesion in the left and right mOTC.

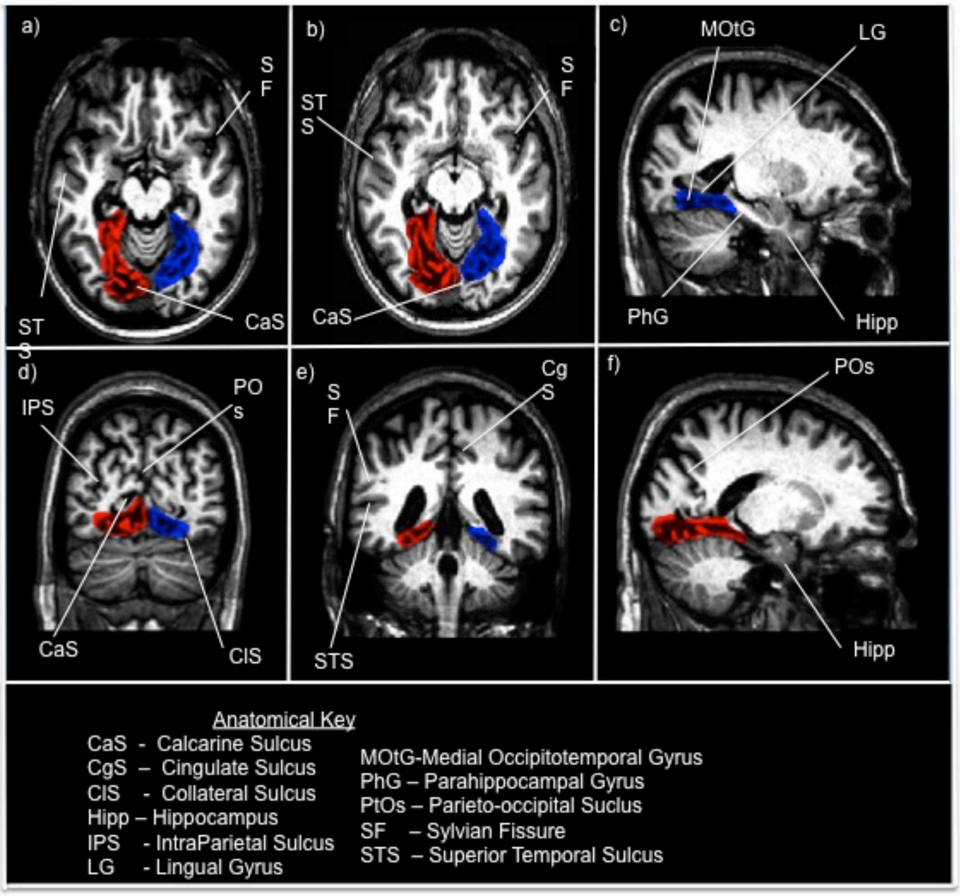

Figure 4.1: *Lesion anatomy. T1 weighted, atlas registered axial (a and b), coronal slices (d and e) and sagittal slices (c and f) illustrate the extent of ischemic damage in the left and right medial Occipito-Temporal cortex. Abnormal tissue in the left and right hemisphere is highlighted in blue and red, respectively.*

4.3.3 Stimuli and experimental procedures

We administered a series of three behavioural experiments to test specific aspects of the participants' abilities to bind spatial and non-spatial information under delayed (i.e., memory) conditions and under immediate perception conditions, and recall spatial information over varying delays. Specifically, experiment 1 assessed participants' ability to pool visual information into a localised centroid judgement. Experiment 2 assessed participants' ability to bind the shape, location and colour of objects stored in WM. Finally, experiment 3 assessed the effects of varying delays on both the binding of colour and space, and on the precision of spatial recall.

For all three experiments, computer-based testing took place in a dark room; participants sat comfortably, unrestrained, 85cm in front of an LCD screen (NEC LCD3210). Unless otherwise specified, custom-coded Matlab scripts (Mathworks, 2014a), using a set of freely available routines designed to facilitate the coding of visual experiments (Brainard, 1997; Kleiner & Brainard, 2007; Pelli, 1997), controlled the experiments and generated the displays, and unless otherwise specified, scripts were executed from an Apple iMac 10.

4.3.3.1 Experiment 1: Centroid estimation

This experiment assessed participants' ability to localise on the basis of visible targets. Specifically, centroid estimation can be modelled with a simple architecture consisting of a bank of centre-surround visual filters followed by a simple decision rule (Drew, Chubb, & Sperling, 2010). Moreover, generating an estimate of a configuration's average position requires pooling on visual information, which is under the control of selective attention and can be biased by shifts of spatial attention (Drew, Chubb, & Sperling, 2009). This task therefore requires both access to basic visual information as well as the recruitment of attentional mechanisms. Participants estimated the position of the centroid of three visible, non-overlapping white discs. The centroid is the location corresponding to the average position of the discs. The discs' diameter was 0.5°. The discs remained visible until participants had positioned a crosshair shaped cursor at the desired location and clicked the mouse. Following a blank, 1.0s-long interval, a novel set of discs appeared and the procedure repeated. Discs could appear in any of seven canonical locations. These included the screen centre and the vertices of a virtual concentric hexagon, with a side length of 6.87°. An exhaustive enumeration of permutations of three out of seven canonical target locations, minus any combinations where the discs were collinear, determined the sample arrays. Each permutation appeared twice, for a total of sixty-four trials. A pseudorandom, zero mean, circular Gaussian distribution (0.7^0) provided additive jitter for each trial's final disc position. Prior to testing, standardised written task instructions described the centroid to participants as the single point in space where the triangle, whose vertices lay at the discs' locations, would balance in the horizontal plane (Baud-Bovy & Soechting, 2001). The experimenter also provided a visual demonstration, using a cutout triangular shape. Prior to testing, participants completed twenty-five practice trials. At the end of each trial, the reported (in red) and actual (in green) position of the centroid appeared for 2.0s (Fig. 4.2a).

4.3.3.2 Experiment 2: Spatial and non-spatial binding in WM

This experiment assessed participants' ability to bind the shape, location and colour of objects stored in WM. We compared recall of a memorised object's colour, depending on whether the report cue was the object's location or shape. In each trial, an equilateral triangle and a square (side lengths: 2.42° and 1.72°, respectively) appeared side-to-side in the lower half of the screen at an eccentricity of 4.25° along the main diagonal for 2.0s. Each shape had a different colour, which could be red, blue or green. A 200ms pattern mask, and then a 2.0s blank screen, followed the sample display. The recall screen contained three coloured rectangles, 1.0° wide and 3.0° high. They aligned 2.5° above the screen centre, horizontally spaced apart by 9.0°. The outline of one of the two shapes (shape cue), or a bright cross (location cue), identified the target. The shape cue appeared 3.0° below the screen centre. The location cues, which also included a dark cross, appeared at the locations occupied by the two shapes. The participant reported the target colour by placing a cursor over one of the rectangles and clicking the left mouse button (Fig. 4.2b). The mouse click prompted the beginning of a new trial, after a 1.0s blank delay.

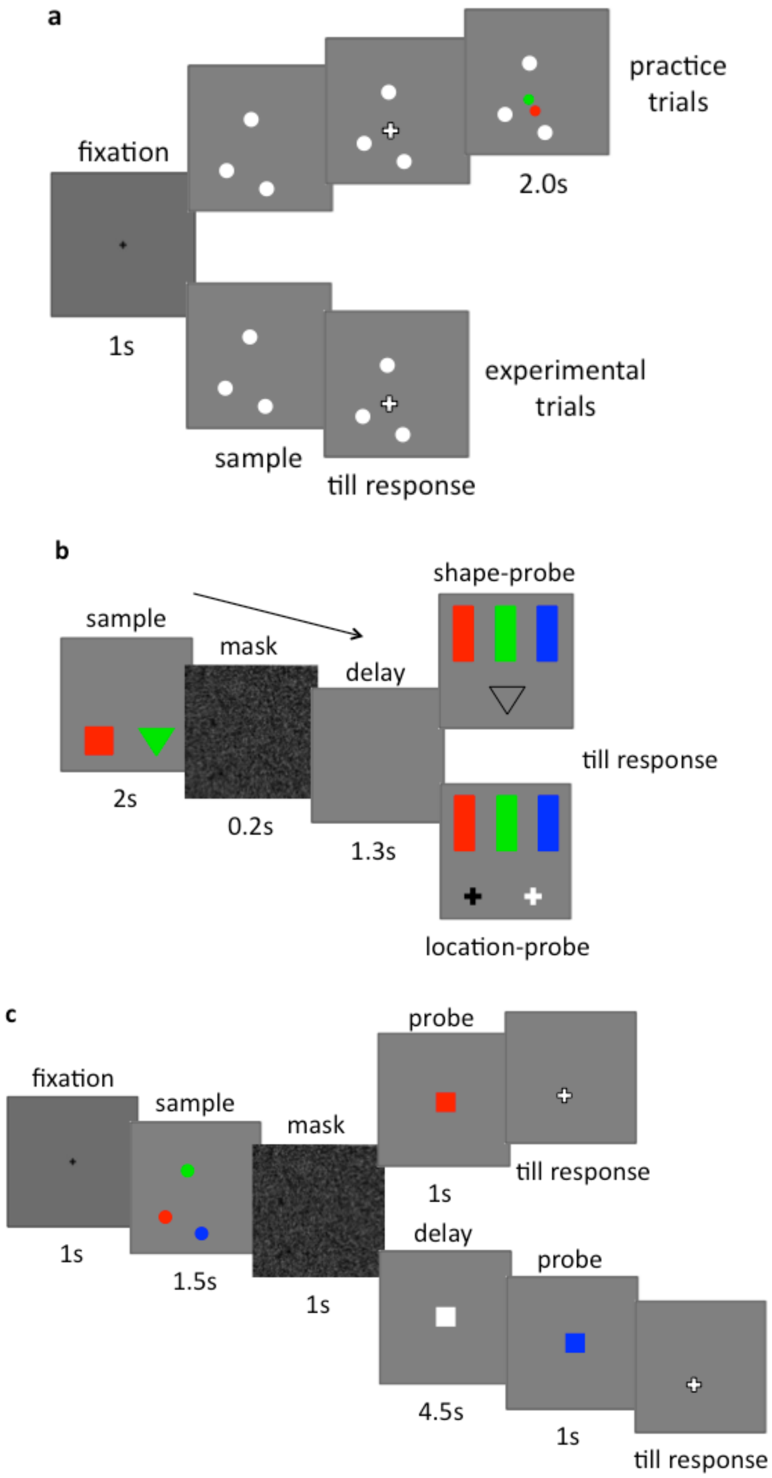

Figure 4.2: *Schematic representations of experimental procedures. a) Trial structure for centroid estimation. The participants placed a cursor at the centroid of the configuration formed by three bright discs. The discs remained visible until the participant made a response by clicking the*

mouse. During practice trials participants received feedback – a red dot appeared at the participants' estimated centroid position and a green one at the actual centroid position. No feedback was available for the experimental trials. b) Trial structure for assessment of spatial and non-spatial binding in working memory. The sample display contained a square and a circle, placed side by side. The two objects were red, blue or green and never had the same colour. After a brief pattern mask and blank delay, three vertical coloured bars appeared as well as a cursor, which was used to indicate the colour of the memory target. In shape trials, a probe whose outline matched the shape of the target identified the target. In location trials, a bright cross was indicated the location of the memory target. c) Trial structure of immediate and delayed spatial WM recall. The sample display contained three coloured discs. The participants had to reproduce the position of one of the discs (the target) after either a 1.0s pattern mask or an additional 4.0s delay. The target was identified by its colour, indicated by a visual probe displayed at the centre of the screen.

Each participant completed ninety trials overall, including both shape and location-cued recalls. Trial order was randomised, minimising participants' ability to predict whether a shape or location-cue would follow.

4.3.3.3 Experiment 3: Delayed spatial recall

This experiment assessed the effects of varying delay periods on a) binding of colour and space, and b) the precision of spatial recall. The sample stimulus contained three coloured discs, 0.8° in diameter. The discs were red, green and blue, and remained visible for 2.0s. A 1.0s long pattern-mask followed the sample. A central report cue (a 0.3° wide white-coloured square) next appeared, and instructed the identity of the target by changing to the relevant colour. The colour change appeared either immediately after the pattern mask or after an additional 4.0s interval. The participants placed a cursor at the recalled target location and clicked the mouse to both record their response and initiate the following trial (Fig. 4.2c). The location of the discs included the centre of the screen and the vertices of a virtual square, at an eccentricity of 6.0°. 2D Gaussian displacement (0.9°) jittered the position of each disc. Each participant completed two blocks of one hundred and twenty trials each.

4.3.4 Data analysis

4.3.4.1 Centroid estimation

Linear regression of reported locations based on the actual location of centroids estimated the systematic and variable components of the error. The systematic error is the component, which is consistently repeated over trials. The variable error is the component, which varies randomly from trial to trial. The literature frequently uses the terms accuracy and precision to refer to the reciprocal values of the systematic and variable errors, respectively. In other words, accurate responses are characterised by small systematic errors and precise responses by small variable errors. The employed modelling procedures and methods of outlier removal are reported in Katshu and d'Avossa (2014). We analysed two metrics of systematic error, displacement (measuring the vector of average bias) and scaling (measuring the linear relationship between reported and actual positions), respectively modelled using the alpha and beta weights of the linear regression. We analysed one metric of variable error, precision, modelled using the variance of the linear regression's residuals. Separate regression models quantified these three metrics for both the azimuth and elevation of judgements.

4.3.4.2 Spatial and non-spatial binding measures

Trials were classified by whether participants reported a) the correct target colour (correct response), b) the colour of the non-target object (binding error), or (c) neither the target nor the non-target object colour (generic error). Each error type (binding and generic) was expressed as a proportion of the total number of trials.

4.3.4.3 Spatial recall precision and binding measurement

Data analysis for Experiment 3 consisted of two stages. First, we identified those trials in which participants had made a binding error. We quantified binding errors as trials where the recalled position was closer to the position of one of the non-target items than to the position of target. We tabulated and removed these trials prior to the second step, in which we estimated the recall systematic and variable error by fitting an affine model to the azimuth and elevation of responses. The model included the target azimuth and elevation as predictors. We used the same procedure used in Experiment 1 on the ensuing residuals to estimate the size of the azimuthal and elevation variable error. Because the patient overestimated, while control participants underestimated, the distance of the recalled target position from screen centre, we adjusted the size of the variable error to account for possible interactions between the variable error and these systematic biases, and thus ensure that the error measures would reflect the resolution of spatial memory, rather than unrelated factors. To this end, we computed the Cramer Rao Lower Bound (CRLB) on the variance of the equivalent unbiased estimator (Stoica & Moses, 1990). This procedure estimates the error variance in a way that discounts the effects of systematic biases on the variable error. The method requires computing the Hessian matrix of the logarithm of the probability density function (PDF) of the reported target location, given its veridical position. The affine model used to estimate the systematic and variable azimuthal and elevational error defined the PDF of the recalled target location conditional on the target location. The CRLB on the variance of the recalled target location is, therefore, a function of the unadjusted error variance and the linear coefficients of the affine.

4.4 Results

4.4.1 Accuracy and precision of centroid estimation

The patient and controls showed different pattern of errors in centroid estimation, localised to the elevation dimension. Figure 4.3 summarises the displacement of centroid estimates. The patient reported the centroid's azimuth displaced -0.08° from its veridical position, on average, while controls reported centroids displaced by -0.07° (95% CI: -0.13 - -0.02), suggesting that the patient and controls showed a similar leftward bias. However, the elevations of the patient's reports were systematically displaced 0.57° above the veridical position of the centroid. This bias was significantly larger than the one found in the controls who showed an average bias of only 0.08° (95% CI = -0.02 – 0.18). The patient scaled the reported centroid azimuth by a factor of 0.99 and elevation by a factor of 0.97, in both cases reflecting an almost perfect linear relationship between reported and actual centroid positions, and in both cases falling within the range of performance shown by healthy controls (azimuth 95% CI: 0.93 – 1.03; elevation 95%CI = 0.92 – 1.02). Finally, the patient's azimuth variable error (0.67°) was within the 95% CI of controls (0.56° - 0.82°). However, his elevation variable error (0.77°) was outside the 95% CI for controls (0.47 - 0.70), suggesting the vertical precision of his centroid judgements was significantly impaired. We conclude that the patient was both systematically biased upward and less precise along the elevation dimension of his centroid reports, potentially in line with his upper visual field defects.

4.4.2 Impaired spatial binding in WM

The patient and controls showed a remarkably different pattern of errors in Experiment 1. Figure 4.4a summarises the proportion of generic error responses; the patient and controls showed similar proportions of generic errors on both location and shape-cued trials. However as can be observed in figure

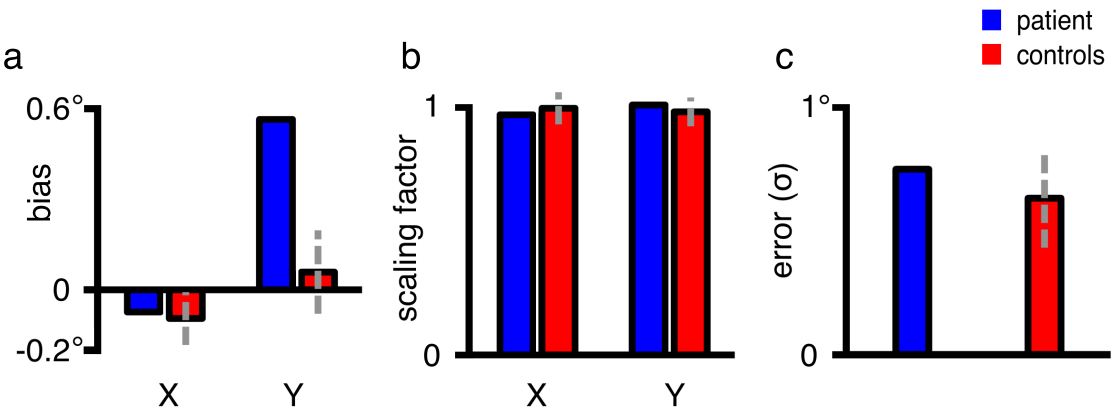

Figure 4.3: *Participants' constant bias, scaling and precision in locating the centroid of the triangular configurations, obtained from the fits and residual errors of an affine model (see Methods). a) Shows group averaged values of the constant bias and b) scaling factor, separately for its horizontal (i.e., azimuth, shown as X) and vertical (i.e., elevation, shown as Y) components. c) The standard deviation of the variable error shown is the square root of the trace of the variable error variance. Error bars are standard error of the mean.*

4.4b, which summarise the proportion of binding error responses, the patient was much more likely to make a binding error when reporting the colour of a target identified by a location probe than by a shape probe ($p < 10^{-6}$ Fisher exact test). The patient was also much more likely to make a binding error than a generic error in the location task ($p < 0.001$, two-tailed binomial test), but not in the shape task ($p = 0.5$). Comparing the groups, the patient's odds ratio of making a binding error in the location relative to shape trials was 60.67 (95% CI: 27.73 - 155.56), while the control group's averaged odds ratio was 0.503 (95% CI: 0.23 - 1.06); this suggests that while the patient was much more likely to make a binding error in the location than shape-probe trials, controls showed a marginally significant opposite tendency. Moreover, the patient's odds ratio of making a binding rather than a generic error in the location vs. shape-cued trials was 29.0 (95% CI: 10.71 - 93.0). For the controls, the group averaged odds ratio was 0.42 (95% CI: 0.21 - 0.83), confirming that the patient was much more

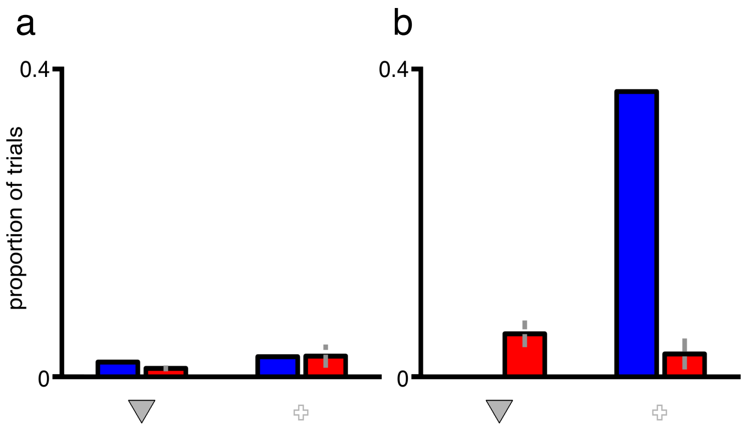

Figure 4.4: *Proportion of generic and binding errors. The bar graphs show the group averaged proportion of a) generic and b) binding errors for the patient (in blue) and controls (in red) following the shape probe (shown as triangle) and location (shown as a cross) probe. Error bars are standard error of the mean.*

likely to make a binding than a generic error in the location than the shape-cued trials, while controls were much more likely to make a binding than a generic error in the shape than the location trials. We conclude that the patient was specifically impaired at binding the colour to the location of the target held in memory, relative to controls.

4.4.3 Delay duration disproportionately affects recall precision

In Experiment 3, the patient and controls differed in terms of overall binding errors and in precision in the longer delay condition. Binding errors are summarised in Figure 4.5a. The proportion of binding errors was 3.75% (95% CI: 2.63 - 4.87) in the control group and 10.83% in the patient, indicating that the patient was much more likely to make a binding error than controls. The odds ratio of making a binding error in the short vs. long delay trials was 1.23 (95% CI: 0.64 - 1.82) for the control group and 1.28 for the patient, suggesting that neither controls nor the patient were more likely to make a binding error in

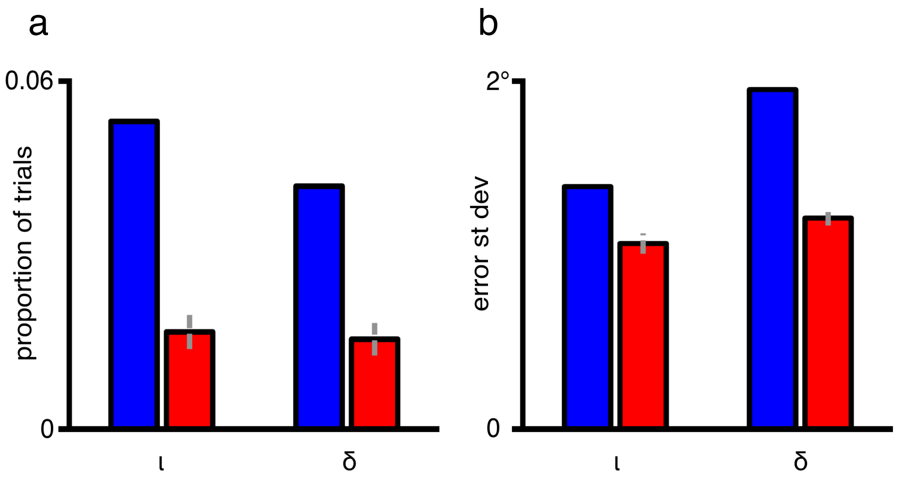

Figure 4.5: *Proportion of binding errors and spatial recall precision over short and long delay periods. a) Shows the group averaged data of the proportion of binding errors, and b) recall precision in immediate (Ι) and delayed (δ) recall trials for the patient and controls. The precision data show the square root of the trace of the error variance. Error bars are standard error of the mean.*

long vs. short delay trials. Recall accuracy showed two types of distortions. Following short delay trials, the control group recalled the target location with a small rightward 0.09° (95% CI: -0.05° – 0.27°) displacement and a larger significant downward -0.34° (95% CI: -0.49° – -0.19°) displacement. The patient instead showed a leftward (-0.21°) and upward (0.12°) displacement. Displacements were similar following the long delay. The control group showed a small rightward 0.07° (95% CI: -0.09 – 0.23) displacement and a larger downward -0.25° (95% CI: -0.11° – -0.4°) displacement. The patient instead showed a leftward (-0.16°) and upward (0.06°) displacement. Linear scaling was summarised using the divergence of the error field (see Methods). In short delay trials, the divergence was -0.27 (95% CI: -0.38 – -0.16) in the control group and 0.03 in the patient. In the long-delay trials, the divergence was -0.29 (95% CI: -0.42 – -0.17) in the control group and 0.14 in the patient, indicating that while controls tended to underestimate the target position relative to the screen centre, the patient overestimated the target distance from the screen centre. Recall precision is summarised in Figure 4.5b. Unadjusted error size was 0.97° (95% CI: 0.87 – 1.07) for the control group and 1.27° for the patient, suggesting that the patient was less precise than the controls. The efficiency of recall in the long-delay compared to short-delay trials was 0.76 (95% CI: 0.67 - 0.87) in the control group and 0.51 in the patient, suggesting that the patient had greater decrements in recall precision with long delays. After the effects of response biases on recall precision were modelled with a CRLB correction, the patient's adjusted recall error was 1.26 while the group average error for controls was 1.16 (95% CI: 1.02 - 1.31). On the other hand, the efficiency of recall at long delays compared to short delays was 0.74 in the control group (95% CI: 0.65- 0.87) while the patient's recall efficiency was only 0.58, suggesting that the patient experienced a decrement in recall precision greater than that experienced by the control group. We conclude that the patient had binding deficits relative to controls that did not interact with delay duration, however longer delays affected the precision of the patient's responses relative to controls.

4.5 Discussion

We tested a patient with bilateral mOTC strokes, limited damage to cortex across the collateral sulcus and complete sparing of Hippocampus and PRC. The patient had presented initially with an acute derangement of attention and WM. Indeed, delirium is frequently observed following ischemic lesions affecting the mOTC (Horenstein et al., 1967; Shih et al., 2007). At the time of testing the patient was no longer delirious, but continued to report on going difficulties navigating, even familiar environments (Epstein et al., 2001; Zola-Morgan et al., 1986). We wanted to ascertain whether subtle deficits in perception and memory could still be uncovered, following the recovery. Indeed, studies in non-human primates have demonstrated persistent deficits in spatial WM following PHC lesions (Bachevalier & Nemanic, 2008; Malkova & Mishkin, 2003).

4.5.1 Impaired spatial binding in WM

The patient showed a remarkable deficit binding objects and features to their location in WM. When the patient reported the colour of one of two objects after a short delay, he was able to do so with great accuracy when the object was cued by its shape. However, when the report object was cued by its location, the patient performance was severely impaired. This impairment could, therefore, not be attributed to either diminished memory for colour or a generalised binding deficit. A recent study reported generalised binding difficulties in individuals recovering from autoimmune Temporal encephalitis, which mainly affects the Hippocampal formation (Pertzov et al., 2013), suggesting that mOTC and PHC lesions sparing the Hippocampus and Perirhinal cortex produce specific deficits in spatial binding, while lesions to other regions of the medial Temporal lobe can result in more generalised binding deficits. Animal and patient studies have indeed shown impairments in forming object place associations in WM following lesions in both Hippocampus and Perirhinal cortex (Bachevalier & Nemanic, 2008; Milner, Johnsrude, &

Crane, 1997). Whether mOTC carries out spatial binding, provides information that is crucial for spatial binding to other structures or plays a role in maintaining spatially bound representations, remains to be established. More broadly, our findings, which demonstrate that there are specific processes for spatial binding are inconsistent with models of WM, which assume that recall of visual information does not require binding (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001) and provide additional evidence for the fact that there exist specific binding processes in WM (Gorgoraptis, Catalao, Bays, & Husain, 2011; Smyrnis et al., 2005; Wheeler & Treisman, 2002).

Overall, these findings are consistent with the idea that space may play a privileged role in binding perceptual and mnestic information (Treisman & Gelade, 1980; Treisman, 1998; Wheeler & Treisman, 2002) and that it exploits a dedicated circuitry within the human brain, not shared with processes that are used to bind information across other, non-spatial, visual dimensions.

4.5.2 Preserved resolution of spatial information

Could the binding impairments in the patient's performance simply reflect a degraded representation of spatial data? If the patient had lost the ability to gauge the location of objects, or parts thereof, it should not come as a surprise that he would also have lost the ability to bind information spatially, even in the absence of a specific binding impairment. This hypothesis is not supported by our data, however. The patient was able to estimate the centroid of simple dot configurations as precisely as controls, indicating that despite the presence of a visual field defect, the spatial resolution of visual data was not prominently affected. Moreover, the patient was more likely to report the location of a non-target item, when the colour was used to identify the target, suggesting a binding impairment whether space was the report or recall dimension. Finally, binding errors were not affected by the delay between the sample presentation and the recall display, even though the precision of spatial recall diminished with delay, suggesting that binding errors did not reflect the resolution of spatial data. In conclusion, spatial binding was impaired whether it was the report or recall dimension. We conclude that diminished spatial binding is a primary deficit in this patient and it cannot be accounted for by diminished spatial resolution.

4.5.3 Longer delays disproportionately affect the precision, but not binding, of spatial recall

As noted above, the duration of the memory delay did not affect the probability of either the controls or the patient making a binding error in the spatial recall task, suggesting that binding errors do not reflect the temporal decay of a memory trace, contrary to previous suggestions (Zhang & Luck, 2008). A previous study showed that memory encoding results in a small number of binding errors that do not increase with longer memory delays (Gorgoraptis et al., 2011). However, the duration of the memory delay decreased both the patient's and controls' precision in recalling the target position. Moreover, the patient showed a much greater decrement in recall precision between short and long delays, compared to controls. These findings suggest a) that spatial recall draws information from a limited resolution resource (Bays & Husain, 2008), and b) that the capacity of this resource diminishes over time, at a much faster rate in the patient than in the controls. Recall precision is known to decrease with memory delay in both healthy controls (Gorgoraptis et al., 2011; Sheth & Shimojo, 2001; Zhang & Luck, 2008), and disproportionally more so in patients with mOTC lesions, though at longer delay intervals (Ploner et al., 2000). Our study complements these results by showing disproportionate decrements even at shorter delay intervals commonly used in WM tasks.

4.5.4 Correlates of visual field defects

The patient had bilateral upper visual field defects, as a result of the central

OTC strokes, in keeping with the known retinotopic organization of early Visual cortical areas (Miller, Newman, Valérie Biousse, & Kerrison, 2005). The patient showed a strong tendency to report the centroid of three dots sample displays above its true location. This bias probably represents an attentional effect. Hemianopic patients display a bias toward their blind field when judging the centre position of horizontal lines (Barton & Black, 1998; Kerkhoff & Bucher, 2008). Interestingly, the patient in our study also tended to overestimate the distance of the target from the display centre, when recalling single target items from memory, while controls showed the opposite bias (Sheth & Shimojo, 2001). A speculative account for this observation may be drawn from the peculiarity of the retinotiopic organization of mOTC, which shows an expanded representation of eccentric portions of the visual field, compared to lateral OTC (Arcaro, McMains, Singer, & Kastner, 2009; Levy, Hasson, Avidan, Hendler, & Malach, 2001). Thus, the recall bias may reflect attentional compensation for a loss of information regarding eccentric locations.

Chapter 5: Summary and discussion

5.1 Summary

Which representations in visual working memory (vWM) are subject to capacity limitations remains debated. The first set of experiments described in Chapter 2 of this thesis, provided evidence for multiple representations, which included high-resolution local maps and coarse, global representations in vWM. This conclusion challenges traditional models, which have, instead, assumed a single representation. We think that the existence of multiple levels of memory representations may explain recent behavioural and neurophysiological observations well, which the existing models cannot accommodate. The second set of experiments, reported in Chapter 3, demonstrated that long-term memory (LTM) improves spatial working memory (sWM) recall accuracy by providing the location of familiar landmarks. These can be used to encode the location of nearby items. In contrast, we found that the statistics of the memory ensemble, stored in long-term memory, played no major role in facilitating the encoding and recall of novel information in sWM. This finding is at odds with the existing WM models, specifically the slots and resources models, which assume that individual objects or features are stored independently leaving no room for interaction between LTM and WM, while the multiple representation model allows for such an interaction. The findings presented in Chapter 3 also showed that sleep was instrumental in consolidating the location of learnt landmarks in LTM. However, sleep did not lead to any overall improvement in sWM. The final set of experiments, described in Chapter 4, presented novel evidence regarding the role of the parahippocampal cortex (PHC) in binding spatial and non-spatial visual features in WM and maintaining spatial information in WM over longer delays. These findings and their implications on our understanding of WM will be discussed in the next sections in more detail.

5.2 Multiple, local and global, representations in sWM

Contemporary WM models assume that the limited capacity buffers used to store features in visual WM are not tuned to specific features within a dimension, unlike sensory representations which are tuned to specific features, like a particular colour within the chromatic dimension or a particular orientation (Bays & Husain, 2008; Zhang & Luck, 2008). The findings reported in Chapter 2 showed that spatial recall precision varied with target location, indicating that vWM buffers were either tuned to the specific location of a target or that the ability to localize a visual target depends on its location. However, we also found that spatial recall precision scaled divisively with memory load at each target location, confirming that the effects of target location on recall precision arise in memory and did not simply reflect a perceptual effect. These behavioural observations, which indicate that the location of a memorised target may be encoded using mechanism with receptive fields of limited extent, are supported by recent neurophysiological data showing that voxel-wise BOLD activity patterns in early Visual areas during the delay period of a WM task, in which participants had to memorise the orientation of a target, were not only similar to the activation patterns in the presence of a task irrelevant orientated stimulus, but also predicted the specific orientation of the memorised target with a high degree of accuracy (Serences et al., 2009). Others have reported similar observations: the memorised feature of a visual target can be deciphered from the voxel-wise BOLD activity patterns in Visual cortex during the maintenance phase of WM tasks (Harrison & Tong, 2009). This neurophysiological evidence clearly suggests that vWM representations, used to store high-fidelity information about the memorised targets, exploit the same neural representations used for the analysis of sensory data. If so, the behavioural observations, reported in Chapter 2, that spatial recall may depend on spatially tuned mechanisms, becomes readily interpretable. That is, the encoding of spatial data in WM exploits the same neural representations used to localize visual targets perceptually.

An important property of visual perception is that it not only generates individual feature representations, but also the gist or the statistical ensemble of the set of features, like colour, size, number, orientation or spatial frequency, in the display (Chong & Treisman, 2005; Girshick et al., 2011; Huang & Sekuler, 2010; Marchant et al., 2013). The estimated mean from the display not only affects the individual feature perception, but may be generated independently even in the absence of individual feature representations (Corbett & Oriet, 2011). In contrast, current vWM models propose that features belonging to different objects are stored independently of each other (Bays & Husain, 2008; Zhang & Luck, 2008). The results, reported in Chapter 2, show that spatial recall is systematically biased towards the centre of configuration of the memorised items. We interpret this finding as indicating the presence of a coarse representation of the overall configuration of the memory items, besides, fine representations of each memory item by spatially curtailed mechanisms. These inferences are also supported by independent behavioural and electrophysiological evidence. An improvement in change detection accuracy has been observed, in behavioural studies, when configurational information is made available at the time of recall (Jiang et al., 2000). Individual neurons in the posterior Parietal cortex of non-human primates performing a match-to-sample task have been shown to respond to changes in the memory sample in object-centred reference frames, suggesting that the location of individual items is also encoded in relation to the position of the other items held in memory (Chafee et al., 2007). The presence of configuration-centred representations may explain the systematic recall biases towards the centre of the configuration reported in Chapter 2. An alternative explanation of these centripetal biases may be that, besides individual object positions, a mean estimate of the position of memorised objects is also stored in vWM. Such an argument was put forth to explain the averaging bias found when recalling the size of a circle. The recall of a given item's size being pulled towards the mean sample size (Brady & Alvarez, 2011). However, that explanation seems to provide an unlikely account for our findings, since we observed that when the locations of the other memory items were shown at recall the bias was diminished, in contrast to increased centripetal bias, as the ensemble account would predict. Our findings may indicate that configurational effects in the spatial domain are different from configuration effects in other visual dimension such as colour, size, etc. The special status of space in the visual perception and memory has been recognised a long time ago, as well as more recently, and it has been suggested to provide a preferential route for binding other features in perception and episodic memory (Darling et al., 2014; Treisman, 1998; Wheeler & Treisman, 2002; Yates, 1992).

5.3 Neural signals associated with WM

Traditionally, neural activity that persists during the delay period and is modulated by memory load has been regarded as the signature of WM. Both contralateral delay activity (CDA), sustained negative change in voltage contralateral to the memorised targets, and BOLD activity in the Parietal areas during the delay period have been shown to increase with memory load before reaching a plateau around the WM capacity limits (Todd & Marois, 2004, 2005; Vogel & Machizawa, 2004; Vogel et al., 2005). Early versions of the slots model accounted for these observations elegantly. The number of slots utilised increases with the number of memorised objects till all slots are used. If the amplitude of delay period neural activity indexes the number of utilised slots then the delay period activity should plateau as the number of slots is topped. However, both recent versions of the slots model and the resource model posit that all the slots or all of the resource are utilised irrespective of the number of objects to be remembered. Hence, they both fail to explain the neurophysiological data.

Recent functional imaging studies have revealed the complex nature of neural activity associated with vWM, since the memorised targets can be decoded from the voxel-wise BOLD patterns recorded in retinotopic area V1, even in the absence of elevated delay-period BOLD activity, which has previously been regarded as the WM neural signature (Harrison & Tong, 2009; Serences et al., 2009). Interestingly, no memorised target specific information could be obtained from the BOLD activity patterns in Frontal and Parietal areas even though these areas showed the characteristic task-related elevated BOLD activity (Emrich et al., 2013; Riggall & Postle, 2012). While it is difficult to accommodate these findings with the slots or resources model, the multiple representations model may offer a plausible explanation. The BOLD activity patterns in early Visual areas may represent the neural substrate of high-resolution maps that encode locally feature information about individual items. Interestingly, neural normalization based on cross-inhibition among units tuned to different features within a dimension, a basic operation in Visual cortical circuits, may account for load effects on recall precision (Ma et al., 2014).

A puzzling issue with the nature of delay neural activity in Visual cortex is that it does not seem to increase with increase in memory load. One possible explanation is that while the activity of neuronal populations within a receptive field corresponding to a particular feature is synchronised, it is conceivable that the activity of neuronal populations in different receptive fields corresponding to different features within a dimension may not be synchronised with each other, which may explain the absence of WM task-related elevated BOLD activity. On the other hand, coarse configurational representations may be maintained in higher cortical areas, like posterior Parietal cortex. This may account for the fact that individual feature cannot be decoded from BOLD activity patterns there. More importantly, the load effects found in Parietal and Frontal regions may reflect the configurational complexity of the memorised sample, thus accounting for the memory-load dependent increase in neural activity observed there. These proposals, though consistent with the available evidence, remain speculative at the moment and need to be tested.

In the next section, I will discuss the nature of interactions between WM and

LTM and whether the interaction is better accounted for the current WM models or the multiple representation model.

5.4 Landmarks in LTM facilitate WM recall

One of the ways to overcome the limited capacity of WM is to link information to be stored in WM to LTM. Individuals can use this strategy automatically. For example, recall of prose is better than that of random word lists, suggesting that semantic information improves encoding and recall efficiency. However, memory techniques to improve recall can also be honed intentionally and with practice, as the historical *method of loci* suggests (Cicero, 1954; Yates, 1992). The results in Chapter 3 show that spatial information was encoded in WM using as a reference landmarks stored in LTM, thereby facilitating its recall, when the landmark appeared in the recall display. However, no improvement in sWM recall was observed when the memory target was shown at a previously over-memorised location, suggesting that information repeatedly stored in WM does not necessarily end up in LTM or change the resolution of WM for highly repeated patterns. These results can not be explained by the slots or resource models as they assume that objects or features are stored independently (Bays & Husain, 2008; Zhang & Luck, 2008). In contrast, the multiple representation model allows for targets to be referenced to landmarks in LTM (Katshu & d'Avossa, 2014). The resulting configurational representations may then improve the spatial recall.

5.5 Sleep consolidates LTM landmark effects on sWM recall

There is a large body of evidence, behavioural as well as neurophysiological, which has indicated that sleep plays a major role in consolidating declarative, procedural and emotional memories (Diekelmann & Born, 2010). However, whether and how sleep affects WM is not clear. The study reported in Chapter 3 examined whether sleep improved WM performance overall or rather led to specific improvements in recall, possibly mediated by interactions between WM and LTM, as discussed above. We found no overall improvement in WM performance following sleep. However, sleep consolidated the effects of visual landmarks on recall accuracy, even when they were no longer visible in the sample display, suggesting that encoding used an internally generated representation of the landmark stored in LTM. In an earlier study, which used an n-back sWM task placing high demands on executive control, improved performance was attributed to increased WM capacity (Kuriyama et al., 2008). In our study, we did not find any change in recall precision, suggesting that the resolution of WM resources was not greatly affected by our procedure. It is pertinent to mention that our task was very simple and had minimal executive demands. It is conceivable that the improved WM performance observed in the previous study may have reflected sleep related improvements in executive control.

5.6 Medial Occipito-Temporal cortex plays an important role in binding and maintaining spatial information in WM

Electrophysiological studies in animals and functional imaging studies in humans have documented that Visual cortex has a highly modular organisation with different areas processing colour, shape, motion, space, etc. (Hubel & Wiesel, 1974; Schiller, 2010; Smith et al., 2001). Focal lesions can lead to specific deficits in the ability to perceive, e.g. either colour (achromatopsia) or motion (akinetopsia), while other visual perceptual functions are preserved. Object perception is, therefore, thought to be accomplished by processes that bind different features, belonging to the same object, together. This attentional process may use spatial indexes to sort the features (Treisman, 1998). A striking example of binding failure can be seen in patients with Parietal lesions, resulting in Balint's syndrome, who are unable to perceive different features of an object together (Chechlacz & Humphreys, 2014). In contrast to this view, objects rather than features are proposed as the units of storage in vWM.

Accordingly, different features of an object, like colour, shape or location, are stored as a single bound unit in the available slot/s in vWM. This view has been recently challenged by observations that recalling a feature correctly does not predict whether another feature of the same object will also be recalled correctly (Bays et al., 2011). Moreover, functional imaging and lesion studies in humans suggest the role of Hippocampal as well as medial Occipito-Temporal cortex (mOTC) areas in binding spatial as well as non-spatial features in WM (Bachevalier & Nemanic, 2008; Milner et al., 1997; Pertzov et al., 2013). In Chapter 4, we found that lesions in mOTC impaired binding of non-spatial and spatial information in vWM. These findings imply that features, rather than whole objects are the storage units in WM and there must be dedicated mechanisms that bind these features together.

The studies reported in Chapter 4 also show that the decrement in spatial recall precision over time was disproportionately larger in the patient with bilateral mOTC lesions, compared to controls. However, crucially, there was no difference in binding errors between shorter and longer delays in the patient, thereby, confirming that the steeper decline in spatial recall precision was independent of binding errors. These results suggest that mOTC helps in maintaining sWM representations over time.

In summary, the findings from this thesis and previous literature provide behavioural as well as neurophysiological evidence to support the multiple representations model of WM. Different processes, including storage of local and global representations, rehearsal, binding of features and top-down attentional mechanisms, support vWM. These processes are supported by neural substrates including Visual, Parietal, medial Temporal and Frontal areas; each area sub-serving specific function/s with potential functional overlap between different areas.

5.7 Clinical implications of the multiple representation model of WM

Impairments in WM have been documented in a variety of neuropsychiatric disorders, including Schizophrenia, Autism Spectrum Disorders, etc. Most of these studies are based on traditional assessment of WM capacity in terms of number of objects stored. Recently, studies have started looking at more sensitive measurements like precision with which features are stored in WM. However, considering the limitations of slots as well as resources models, which form the theoretical basis for object and precision based WM tests respectively, to explain the behavioural and neurophysiological findings, evidence presented in this thesis supports assessments that incorporate analysing the multiple representations, local high-fidelity as well as coarse configurational, that support vWM. There is evidence to support this proposal, for example in Schizophrenia and ASD. People with schizophrenia (Chen, Nakayama, Levy, Matthysse, & Holzman, 2003; Tibber et al., 2015) and ASD (Koldewyn, Jiang, Weigelt, & Kanwisher, 2013; Kuschner, Bodner, & Minshew, 2009) have been shown to perceive local visual features normally or better than healthy controls, but demonstrate impairments in perception of global configurations. Also, spatial WM impairments have been demonstrated in both Schizophrenia (Park & Gooding, 2014; Saperstein et al., 2006) and ASD (Jiang, Capistrano, & Palm, 2014; Williams, Goldstein, & Minshew, 2006). Analysing both the local, high fidelity as well as coarse, configurational representations could tease apart the underlying nature of WM deficits in these disorders.

References

Aguirre, G. K., Detre, J. A., Alsop, D. C., & D'Esposito, M. (1996). The parahippocampus subserves topographical learning in man. *Cerebral Cortex*, *6*(6), 823–829. http://doi.org/10.1093/cercor/6.6.823

Aminoff, E., Gronau, N., & Bar, M. (2007). The parahippocampal cortex mediates spatial and nonspatial associations. *Cerebral Cortex*, *17*(7), 1493–1503. http://doi.org/10.1093/cercor/bhl078

Aminoff, E. M., Kveraga, K., & Bar, M. (2013). The role of the parahippocampal cortex in cognition. *Trends in Cognitive Sciences*, 17(8):379-90. http://doi.org/10.1016/j.tics.2013.06.009

Arcaro, M. J., McMains, S. A., Singer, B. D., & Kastner, S. (2009). Retinotopic organization of human ventral visual cortex. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *29*(34), 10638–52. http://doi.org/10.1523/JNEUROSCI.2807-09.2009

Aristotle. (1984). *The complete works of Aristotle: The revised Oxford translation*. (J. Barnes, Ed.) (Volume 1). New Jersey: Princeton University Press.

Awh, E., Vogel, E. K., & Oh, S.-H. (2006). Interactions between attention and working memory. *Neuroscience*, *139*(1), 201–8. http://doi.org/10.1016/j.neuroscience.2005.08.023

Axmacher, N., Mormann, F., Fernández, G., Cohen, M. X., Elger, C. E., & Fell, J. (2007). Sustained neural activity patterns during working memory in the human medial temporal lobe. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *27*, 7807–7816. http://doi.org/10.1523/JNEUROSCI.0962-07.2007

Bachevalier, J., & Nemanic, S. (2008). Memory for spatial location and object-place associations are differently processed by the hippocampal formation, parahippocampal areas TH/TF and perirhinal cortex. *Hippocampus*, *18*(1), 64–80. http://doi.org/10.1002/hipo.20369

Baddeley, A. (1996). Exploring the central executive. *Quarterly Journal of*

Experimental Psychology, *49A*(1), 5–28. http://doi.org/10.1080/713755608

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*. http://doi.org/10.1016/S1364-6613(00)01538-2

Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews. Neuroscience*, *4*(October), 829–839. http://doi.org/10.1038/nrn1201

Baddeley, A. (2012). Working memory: theories, models, and controversies. *Annual Review of Psychology*, *63*, 1–29. http://doi.org/10.1146/annurev-psych-120710-100422

Baddeley, A. D., & Hitch, G. (1974). Working Memory. In G. A. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Volume 8, pp. 47–89). New York: Academic Press.

Baddeley, A., & Larsen, J. D. (2007). The phonological loop: Some answers and some questions. *Quarterly Journal of Experimental Psychology*, 60(4), 512-18. http://doi.org/10.1080/17470210601147663

Bar, M., & Aminoff, E. (2003). Cortical analysis of visual context. *Neuron*, *38*(2), 347–358. http://doi.org/10.1016/S0896-6273(03)00167-3

Barton, J. J., & Black, S. E. (1998). Line bisection in hemianopia. *Journal of Neurology, Neurosurgery, and Psychiatry*, *64*, 660–662. http://doi.org/10.1136/jnnp.66.1.121a

Baud-Bovy, G., & Soechting, J. (2001). Visual localization of the center of mass of compact, asymmetric, two-dimensional shapes. *Journal of Experimental Psychology. Human Perception and Performance*, 27(3):692-706. http://doi.org/10.1037/0096-1523.27.3.692

Bays, P. M., Gorgoraptis, N., Wee, N., Marshall, L., & Husain, M. (2011). Temporal dynamics of encoding, storage, and reallocation of visual working memory. *Journal of Vision*, *11*(10), 1–15. http://doi.org/10.1167/11.10.6

Bays, P. M., & Husain, M. (2008). Dynamic shifts of limited working memory resources in human vision. *Science (New York, N.Y.)*, *321*(5890), 851–4. http://doi.org/10.1126/science.1158023

Bays, P. M., Wu, E. Y., & Husain, M. (2011). Storage and binding of object features in visual working memory. *Neuropsychologia*, *49*(6), 1622–31. http://doi.org/10.1016/j.neuropsychologia.2010.12.023

Brady, T. F., & Alvarez, G. A. (2011). Hierarchical encoding in visual working memory: ensemble statistics bias memory for individual items. *Psychological Science*, *22*(3), 384–92. http://doi.org/10.1177/0956797610397956

Brady, T. F., Konkle, T., & Alvarez, G. A. (2011). A review of visual memory capacity: Beyond individual items and toward structured representations. *Journal of Vision*, *11*(5), 4. http://doi.org/10.1167/11.5.4

Brady, T. F., Konkle, T., Gill, J., Oliva, A., & Alvarez, G. a. (2013). Visual long-term memory has the same limit on fidelity as visual working memory. *Psychological Science*, *24*(6), 981–90. http://doi.org/10.1177/0956797612465439

Brady, T. F., & Oliva, A. (2008). Statistical learning using real-world scenes: Extracting categorical regularities without conscious intent: Research article. *Psychological Science*, *19*(7), 678–685. http://doi.org/10.1111/j.1467-9280.2008.02142.x

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10(4):433-6.

Chafee, M. V, Averbeck, B. B., & Crowe, D. a. (2007). Representing spatial relationships in posterior parietal cortex: single neurons code object-referenced position. *Cerebral Cortex (New York, N.Y. : 1991)*, *17*(12), 2914–32. http://doi.org/10.1093/cercor/bhm017

Chafee, M. V, Crowe, D. A., Averbeck, B. B., & Georgopoulos, A. P. (2005). Neural correlates of spatial judgement during object construction in parietal cortex. *Cerebral Cortex (New York, N.Y. : 1991)*, *15*(9), 1393–413. http://doi.org/10.1093/cercor/bhi021

Chechlacz, M., & Humphreys, G. W. (2014). The enigma of Bálint's syndrome: neural substrates and cognitive deficits. *Frontiers in Human Neuroscience*, *8*, 123. http://doi.org/10.3389/fnhum.2014.00123

Chen, Y., Nakayama, K., Levy, D., Matthysse, S., & Holzman, P. (2003).

Processing of global, but not local, motion direction is deficient in schizophrenia. *Schizophrenia Research*, *61*(2-3), 215–27. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12729873

Chong, S. C., & Treisman, A. (2005). Statistical processing: Computing the average size in perceptual groups. *Vision Research*, *45*(7), 891–900. http://doi.org/10.1016/j.visres.2004.10.004

Christophel, T. B., Hebart, M. N., & Haynes, J.-D. (2012). Decoding the Contents of Visual Short-Term Memory from Human Visual and Parietal Cortex. *Journal of Neuroscience*, *32*(38), 12983–12989. http://doi.org/10.1523/JNEUROSCI.0184-12.2012

Cicero. (1954). *Rhetorica ad Herennium*. (H. Caplan, Ed.). Massachusetts: Harvard University Press.

Corbett, J. E., & Oriet, C. (2011). The whole is indeed more than the sum of its parts: Perceptual averaging in the absence of individual item representation. *Acta Psychologica*, *138*(2), 289–301. http://doi.org/10.1016/j.actpsy.2011.08.002

Corkin, S., Amaral, D. G., González, R. G., Johnson, K. a, Hyman, B. T., Gonzalez, R. G., … Hyman, B. T. (1997). H. M.'s medial temporal lobe lesion: findings from magnetic resonance imaging. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *17*(10), 3964–3979.

Corkin, S., Kosslyn, S. M., & Andersen, R. A. (1992). Lasting consequences of bilateral medial temporal lobectomy: Clinical course and experimental findings in H. M. In *Frontiers in cognitive neuroscience.* (pp. 516–526).

Courtney, S. M., Ungerleider, L. G., Keil, K., & Haxby, J. V. (1997). Transient and sustained activity in a distributed neural system for human working memory. *Nature*, 386(6625):608-11. http://doi.org/10.1038/386608a0

Cowan, N. (2010). The Magical Mystery Four: How Is Working Memory Capacity Limited, and Why? *Current Directions in Psychological Science*, *19*(1), 51–57. http://doi.org/10.1177/0963721409359277

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: A meta-analysis. *Psychonomic Bulletin & Review*, *3*(4), 422–433. http://doi.org/10.3758/BF03214546

Darling, S., Parker, M. J., Goodall, K. E., Havelka, J., & Allen, R. J. (2014). Visuospatial bootstrapping: Implicit binding of verbal working memory to visuospatial representations in children and adults. *Journal of Experimental Child Psychology*, *119*, 112–119. http://doi.org/10.1016/j.jecp.2013.10.004

Delvenne, J.-F. (2005). The capacity of visual short-term memory within and between hemifields. *Cognition*, *96*, 79–88. http://doi.org/10.1016/j.cognition.2004.12.007

Diana, R. A., Yonelinas, A. P., & Ranganath, C. (2007). Imaging recollection and familiarity in the medial temporal lobe: a three-component model. *Trends in Cognitive Sciences*, *11*(9), 379–386. http://doi.org/10.1016/j.tics.2007.08.001

Diedrichsen, J., Werner, S., Schmidt, T., & Trommershäuser, J. (2004). Immediate spatial distortions of pointing movements induced by visual landmarks. *Perception & Psychophysics*, *66*(1), 89–103. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15095943

Diekelmann, S., & Born, J. (2010). The memory function of sleep. *Nature Reviews. Neuroscience*, *11*(2), 114–26. http://doi.org/10.1038/nrn2762

Drew, S. a, Chubb, C. F., & Sperling, G. (2010). Precise attention filters for Weber contrast derived from centroid estimations. *Journal of Vision*, *10*, 20. http://doi.org/10.1167/10.10.20

Drew, S., Chubb, C., & Sperling, G. (2009). Quantifying attention: Attention filtering in centroid estimations. *Journal of Vision*, *9*(8), 229–229. http://doi.org/10.1167/9.8.229

Düzel, E., Habib, R., Rotte, M., Guderian, S., Tulving, E., & Heinze, H. (2003). Human hippocampal and parahippocampal activity during visual associative recognition memory for spatial and nonspatial stimulus configurations. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *23*(28), 9439–9444. http://doi.org/23/28/9439 [pii]

Eichenbaum, H., Sauvage, M., Fortin, N., Komorowski, R., & Lipton, P. (2012).

Towards a functional organization of episodic memory in the medial temporal lobe. *Neuroscience and Biobehavioral Reviews*. http://doi.org/10.1016/j.neubiorev.2011.07.006

Eichenbaum, H., Yonelinas, A. P., & Ranganath, C. (2007). The medial temporal lobe and recognition memory. *Annual Review of Neuroscience*, *30*, 123–52. http://doi.org/10.1146/annurev.neuro.30.051606.094328

Emrich, S. M., Riggall, A. C., LaRocque, J. J., & Postle, B. R. (2013). Distributed patterns of activity in sensory cortex reflect the precision of multiple items maintained in visual short-term memory. *The Journal of Neuroscience*, *33*(15), 6516–6523. http://doi.org/10.1523/JNEUROSCI.5732-12.2013

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, a R. (1999). Working memory, short-term memory, and general fluid intelligence: a latent-variable approach. *Journal of Experimental Psychology. General*, *128*(3), 309–331. http://doi.org/10.1037/0096-3445.128.3.309

Epstein, R. A. (2008). Parahippocampal and retrosplenial contributions to human spatial navigation. *Trends in Cognitive Sciences*, 12(10):388-96. http://doi.org/10.1016/j.tics.2008.07.004

Epstein, R., Deyoe, E. a, Press, D. Z., Rosen, a C., & Kanwisher, N. (2001). Neuropsychological evidence for a topographical learning mechanism in parahippocampal cortex. *Cognitive Neuropsychology*, *18*(6), 481–508. http://doi.org/10.1080/02643290125929

Epstein, R., Harris, A., Stanley, D., & Kanwisher, N. (1999). The parahippocampal place area: Recognition, navigation, or encoding? *Neuron*, *23*(1), 115–125. http://doi.org/10.1016/S0896-6273(00)80758-8

Epstein, R., & Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature*, *392*(6676), 598–601. http://doi.org/10.1038/33402

Ericsson, K., & Kintsch, W. (1995). Long-term working memory. *Psychological Review*, *102*(2), 211–245. http://doi.org/10.1037/0033-295X.102.2.211

Ezzyat, Y., & Olson, I. R. (2008). The medial temporal lobe and visual working memory: comparisons across tasks, delays, and visual similarity. *Cognitive, Affective & Behavioral Neuroscience*, *8*(1), 32–40.

http://doi.org/10.3758/CABN.8.1.32

Finke, C., Braun, M., Ostendorf, F., Lehmann, T. N., Hoffmann, K. T., Kopp, U., & Ploner, C. J. (2008). The human hippocampal formation mediates short-term memory of colour-location associations. *Neuropsychologia*, *46*(2), 614–623. http://doi.org/10.1016/j.neuropsychologia.2007.10.004

Fortenbaugh, F. C., Sanghvi, S., Silver, M. A., & Robertson, L. C. (2012). Exploring the edges of visual space: the influence of visual boundaries on peripheral localization. *Journal of Vision*, *12*(2), 1–18. http://doi.org/10.1167/12.2.19

Franconeri, S. L., Alvarez, G. A., & Cavanagh, P. (2013). Flexible cognitive resources : competitive content maps for attention and memory. *Trends in Cognitive Sciences*, *17*(3), 134–141. http://doi.org/10.1016/j.tics.2013.01.010

Fuentemilla, L., Miró, J., Ripollés, P., Vilà-Balló, A., Juncadella, M., Castañer, S., … Rodríguez-Fornells, A. (2013). Hippocampus-dependent strengthening of targeted memories via reactivation during sleep in humans. *Current Biology*, *23*(18), 1769–1775. http://doi.org/10.1016/j.cub.2013.07.006

Funahashi, S., Bruce, J., & Goldman-Rakic, P. S. (1989). Mnemonic Coding of Visual Space in the Monkey ' s Dorsolateral Prefrontal Cortex. *Journal of Neurophysiology*, 61(2):331-49.

Fuster, J. M., & Alexander, G. E. (1971). Neuron Activity Related to Short-Term Memory. *Science*, 173(3997):652-4. http://doi.org/10.1126/science.173.3997.652

Gais, S., Lucas, B., & Born, J. (2006). Sleep after learning aids memory recall. *Learning & Memory*, *13*(3), 259–62. http://doi.org/10.1101/lm.132106

Girshick, A. R., Landy, M. S., & Simoncelli, E. P. (2011). Cardinal rules: visual orientation perception reflects knowledge of environmental statistics. *Nature Neuroscience*, *14*(7), 926–932. http://doi.org/10.1038/nn.2831

Gobet, F., Lane, P. C. R., Croker, S., Cheng, P. C.-H., Jones, G., Oliver, I., & Pine, J. M. (2001). Chunking mechanisms in human learning. *Trends in*

Cognitive Sciences, *5*(6), 236–243. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11390294

Gorgoraptis, N., Catalao, R. F. G., Bays, P. M., & Husain, M. (2011). Dynamic updating of working memory resources for visual objects. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *31*(23), 8502–11. http://doi.org/10.1523/JNEUROSCI.0208-11.2011

Habib, M., & Sirigu, A. (1987). Pure topographical disorientation: a definition and anatomical basis. *Cortex*, *23*(1), 73–85. http://doi.org/10.1016/S0010-9452(87)80020-5

Hannula, D. E., & Ranganath, C. (2008). Medial Temporal Lobe Activity Predicts Successful Relational Memory Binding. *Journal of Neuroscience*, *28*(1), 116–124. http://doi.org/10.1523/JNEUROSCI.3086-07.2008

Hannula, D. E., Tranel, D., & Cohen, N. J. (2006). The Long and the Short of It: Relational Memory Impairments in Amnesia, Even at Short Lags. *Journal of Neuroscience*, *26*(32), 8352–8359. http://doi.org/10.1523/JNEUROSCI.5222-05.2006

Harrison, S. A., & Tong, F. (2009). Decoding reveals the contents of visual working memory in early visual areas. *Nature*, *458*(7238), 632–635. http://doi.org/10.1038/nature07832

Horenstein, S., Chamberlain, W., & Conomy, J. (1967). Infarctions of the fusiform and calcarine regions with agitated delirium and hemianopsia. *Trans Am Neurol Assoc*, *92*, 85–89.

Howard, L. R., Kumaran, D., Ólafsdóttir, H. F., & Spiers, H. J. (2011). Double dissociation between hippocampal and parahippocampal responses to object-background context and scene novelty. *The Journal of Neuroscience*, *31*(14), 5253–5261. http://doi.org/10.1523/JNEUROSCI.6055-10.2011

Hu, Y., & Goodale, M. A. A. (2000). Grasping after a delay shifts size-scaling from absolute to relative metrics. *Journal of Cognitive Neuroscience*, *12*(5), 856–868.

Huang, J., & Sekuler, R. (2010). Distortions in recall from visual memory : Two classes of attractors at work Jie Huang. *Journal of Vision*, *10(2)*(24), 1–27. http://doi.org/10.1167/10.2.24.Introduction

Hubbard, T. L., & Ruppel, S. E. (2000). Spatial memory averaging, the landmark attraction effect, and representational gravity. *Psychological Research*, *64*(1), 41–55. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11109866

Hubel, D. H., & Wiesel, T. N. (1974). Uniformity of monkey striate cortex: a parallel relationship between field size, scatter, and magnification factor. *The Journal of Comparative Neurology*, *158*(3), 295–305. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/4436457

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(19), 6829–6833. http://doi.org/10.1073/pnas.0801268105

Ji, D., & Wilson, M. A. (2007). Coordinated memory replay in the visual cortex and hippocampus during sleep. *Nature Neuroscience*, *10*(1), 100–107. http://doi.org/10.1038/nn1825

Jiang, Y. V, Capistrano, C. G., & Palm, B. E. (2014). Spatial working memory in children with high-functioning autism: intact configural processing but impaired capacity. *Journal of Abnormal Psychology*, *123*(1), 248–57. http://doi.org/10.1037/a0035420

Jiang, Y. V, Olson, I. R., & Chun, M. M. (2000). Organization of visual short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(3), 683–702. http://doi.org/10.1037/0278-7393.26.3.683

Katshu, M. Z. U. H., & d'Avossa, G. (2014). Fine-grained, local maps and coarse, global representations support human spatial working memory. *PloS One*, *9*(9), e107969. http://doi.org/10.1371/journal.pone.0107969

Kerkhoff, G., & Bucher, L. (2008). Line bisection as an early method to assess homonymous hemianopia. *Cortex*, *44*(2), 200–205. http://doi.org/10.1016/j.cortex.2006.07.002

Kleiner M, Brainard, D., & Pelli, D. (2007). What's new in Psychtoolbox-3?

Perception 36 ECVP Abstract Supplement.

Koldewyn, K., Jiang, Y. V, Weigelt, S., & Kanwisher, N. (2013). Global/local processing in autism: not a disability, but a disinclination. *Journal of Autism and Developmental Disorders*, *43*(10), 2329–40. http://doi.org/10.1007/s10803-013-1777-z

Konkle, T., & Oliva, A. (2012). A Real-World Size Organization of Object Responses in Occipitotemporal Cortex. *Neuron*, *74*(6), 1114–1124. http://doi.org/10.1016/j.neuron.2012.04.036

Kubota, K., & Niki, H. (1971). Prefrontal cortical unit activity and delayed alternation performance in monkeys. *Journal of Neurophysiology*, *34*(3), 337–347.

Kuriyama, K., Mishima, K., Suzuki, H., Aritake, S., & Uchiyama, M. (2008). Sleep accelerates the improvement in working memory performance. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *28*(40), 10145–50. http://doi.org/10.1523/JNEUROSCI.2039-08.2008

Kuschner, E. S., Bodner, K. E., & Minshew, N. J. (2009). Local vs. global approaches to reproducing the Rey Osterrieth Complex Figure by children, adolescents, and adults with high-functioning autism. *Autism Research : Official Journal of the International Society for Autism Research*, *2*(6), 348–58. http://doi.org/10.1002/aur.101

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity?! *Intelligence*, *14*(4), 389–433. http://doi.org/10.1016/S0160-2896(05)80012-1

Lee, A. C. H., Bussey, T. J., Murray, E. A., Saksida, L. M., Epstein, R. A., Kapur, N., … Graham, K. S. (2005). Perceptual deficits in amnesia: Challenging the medial temporal lobe “mnemonic” view. *Neuropsychologia*, *43*(1), 1–11. http://doi.org/10.1016/j.neuropsychologia.2004.07.017

Lee, S.-H., Kravitz, D. J., & Baker, C. I. (2013). Goal-dependent dissociation of visual and prefrontal cortices during working memory. *Nature Neuroscience*, *16*(8), 997–9. http://doi.org/10.1038/nn.3452

Levy, I., Hasson, U., Avidan, G., Hendler, T., & Malach, R. (2001). Center–periphery organization of human object areas. *Nature Neuroscience*, *4*(5), 533–539. http://doi.org/10.1038/87490

Logie, R. H. (2011). The Functional Organization and Capacity Limits of Working Memory. *Current Directions in Psychological Science*, *20*(4), 240–245. http://doi.org/10.1177/0963721411415340

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–81. http://doi.org/10.1038/36846

Ma, W. J., Husain, M., & Bays, P. M. (2014). Changing concepts of working memory. *Nature Neuroscience*, *17*(3), 347–356. http://doi.org/10.1038/nn.3655

Malkova, L., & Mishkin, M. (2003). One-trial memory for object-place associations after separate lesions of hippocampus and posterior parahippocampal region in the monkey. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *23*(5), 1956–1965.

Marchant, A. P., Simons, D. J., & de Fockert, J. W. (2013). Ensemble representations: Effects of set size and item heterogeneity on average size perception. *Acta Psychologica*, *142*(2), 245–250. http://doi.org/10.1016/j.actpsy.2012.11.002

McCarthy, G., Blamire, a M., Puce, a, Nobre, a C., Bloch, G., Hyder, F., … Shulman, R. G. (1994). Functional magnetic resonance imaging of human prefrontal cortex activation during a spatial working memory task. *Proceedings of the National Academy of Sciences of the United States of America*, *91*(18), 8690–4. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=44672&tool=pmcentrez&rendertype=abstract

Medina, J. L., Chokroverty, S., & Rubino, F. A. (1977). Syndrome of agitated delirium and visual impairment: a manifestation of medial temporo-occipital infarction. *Journal of Neurology, Neurosurgery, and Psychiatry*, *40*(9), 861–4. http://doi.org/10.1136/jnnp.40.9.861

Mednick, S. C., Nakayama, K., Cantero, J. L., Atienza, M., Levin, A. A., Pathak, N., & Stickgold, R. (2002). The restorative effect of naps on perceptual deterioration. *Nature Neuroscience*, 5(7):677-81. http://doi.org/10.1038/nn864

Mednick, S., Nakayama, K., & Stickgold, R. (2003). Sleep-dependent learning: a nap is as good as a night. *Nature Neuroscience*, *6*(7), 697–698. http://doi.org/10.1038/nn1078

Miller, G. A., Galanter, E., & Pribram, K. H. (1960). *Plans and the Structure of Behavior* (Vol. 19). New York: Henry Holt and Co. Retrieved from http://www.jstor.org/stable/3008635?origin=crossref

Milner, B., Corkin, S., & Teuber, H.-L. (1968). Further analysis of the hippocampal amnesic syndrome: 14-year follow-up study of H.M. *Neuropsychologia*, *6*(3), 215–234. http://doi.org/10.1016/0028-3932(68)90021-3

Milner, B., Johnsrude, I., & Crane, J. (1997). Right medial temporal-lobe contribution to object-location memory. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *352*(1360), 1469–1474. http://doi.org/10.1098/rstb.1997.0133

Mishkin, M. (1978). Memory in monkeys severely impaired by combined but not by separate removal of amygdala and hippocampus. *Nature*, *273*(5660), 297–8. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/418358

Moser, E. I., Kropff, E., & Moser, M.-B. (2008). Place cells, grid cells, and the brain's spatial representation system. *Annual Review of Neuroscience*, *31*, 69–89. http://doi.org/10.1146/annurev.neuro.31.061307.090723

Murray, E. a, Bussey, T. J., & Saksida, L. M. (2007). Visual perception and memory: a new view of medial temporal lobe function in primates and rodents. *Annual Review of Neuroscience*, *30*, 99–122. http://doi.org/10.1146/annurev.neuro.29.051605.113046

Miller, N. R., Newman, N. J., Biousse, V., & Kerrison, J. B. (2005). *Walsh and Hoyt's Clinical Neuro-Ophthalmology*. Philadelphia: Lippincott Williams & Wilkins. http://doi.org/10.1056/NEJM200508113530624

Nelson, T. O., & Chaiklin, S. (1980). Immediate memory for spatial location. *Journal of Experimental Psychology. Human Learning and Memory*, *6*(5), 529–45.

O'Craven, K. M., & Kanwisher, N. (2000). Mental imagery of faces and places activates corresponding stiimulus-specific brain regions. *Journal of Cognitive Neuroscience*, *12*(6), 1013–23. http://doi.org/10.1162/08989290051137549

Olson, I. R., Moore, K. S., Stark, M., & Chatterjee, A. (2006). Visual working memory is impaired when the medial temporal lobe is damaged. *Journal of Cognitive Neuroscience*, *18*(7), 1087–97. http://doi.org/10.1162/jocn.2006.18.7.1087

Park, S., & Gooding, D. C. (2014). Working memory impairment as an endophenotypic marker of a schizophrenia diathesis. *Schizophrenia Research: Cognition*, *1*(3), 127–136. http://doi.org/10.1016/j.scog.2014.09.005

Peigneux, P., Laureys, S., Fuchs, S., Collette, F., Perrin, F., Reggers, J., … Maquet, P. (2004). Are spatial memories strengthened in the human hippocampus during slow wave sleep? *Neuron*, *44*(3), 535–545. http://doi.org/10.1016/j.neuron.2004.10.007

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: transforming numbers into movies. *Spatial Vision,* 10:437-442.

Pertzov, Y., Miller, T. D., Gorgoraptis, N., Caine, D., Schott, J. M., Butler, C., & Husain, M. (2013). Binding deficits in memory following medial temporal lobe damage in patients with voltage-gated potassium channel complex antibody-associated limbic encephalitis. *Brain*, *136*(8), 2474–2485. http://doi.org/10.1093/brain/awt129

Piekema, C., Kessels, R. P. C., Mars, R. B., Petersson, K. M., & Fernández, G. (2006). The right hippocampus participates in short-term memory maintenance of object-location associations. *NeuroImage*, *33*(1), 374–382. http://doi.org/10.1016/j.neuroimage.2006.06.035

Plihal, W., & Born, J. (1997). Effects of early and late nocturnal sleep on declarative and procedural memory. *Journal of Cognitive Neuroscience*, *9*(4), 534–47. http://doi.org/10.1162/jocn.1997.9.4.534

Plihal, W., & Born, J. (1999). Effects of early and late nocturnal sleep on priming and spatial memory. *Psychophysiology*, *36*(5), 571–582. http://doi.org/10.1111/1469-8986.3650571

Ploner, C. J., Gaymard, B. M., Rivaud-Péchoux, S., Baulac, M., Clémenceau, S., Samson, S., & Pierrot-Deseilligny, C. (2000). Lesions affecting the parahippocampal cortex yield spatial memory deficits in humans. *Cerebral Cortex (New York, N.Y. : 1991)*, *10*(12), 1211–6. http://doi.org/10.1093/cercor/10.12.1211

Poirier, M., Dhir, P., Tehan, G., & Hampton, J. (2011). *The Influence of Semantic Memory on Verbal Short-term Memory*. (B. Kokinov, A. Karmiloff-Smith, & N. J. Nersessian, Eds.) (European P). Sofia: New Bulgarian University Press.

Ranganath, C., & D'Esposito, M. (2001). Medial temporal lobe activity associated with active maintenance of novel information. *Neuron*, *31*(5), 865–873. http://doi.org/10.1016/S0896-6273(01)00411-1

Riggall, A. C., & Postle, B. R. (2012). The relationship between working memory storage and elevated activity as measured with functional magnetic resonance imaging. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *32*(38), 12990–8. http://doi.org/10.1523/JNEUROSCI.1892-12.2012

Romero, K., & Moscovitch, M. (2012). Episodic memory and event construction in aging and amnesia. *Journal of Memory and Language*, *67*(2), 270–284. http://doi.org/10.1016/j.jml.2012.05.002

Saperstein, A. M., Fuller, R. L., Avila, M. T., Adami, H., McMahon, R. P., Thaker, G. K., & Gold, J. M. (2006). Spatial working memory as a cognitive endophenotype of schizophrenia: assessing risk for pathophysiological dysfunction. *Schizophrenia Bulletin*, *32*(3), 498–506. http://doi.org/10.1093/schbul/sbj072

Schiller, P. H. (2010). Parallel information processing channels created in the retina. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(40), 17087–17094. http://doi.org/10.1073/pnas.1011782107

Schmidley, J. W., & Messing, R. O. (1984). Agitated confusional states in patients with right hemisphere infarctions. *Stroke*, *15*(5), 883–885. http://doi.org/10.1161/01.STR.15.5.883

Scoville, W. B., & Milner, B. (1957). Loss of recentmemory after bilateral hippocampal lesions. *Journal of Neurology, Neurosurgery & Psychiatry*, *20*(1), 11–21. http://doi.org/10.1136/jnnp.20.1.11

Serences, J. T., Ester, E. F., Vogel, E. K., & Awh, E. (2009). Stimulus-specific delay activity in human primary visual cortex. *Psychological Science*, *20*(2), 207–14. http://doi.org/10.1111/j.1467-9280.2009.02276.x

Sheth, B. R., & Shimojo, S. (2001). Compression of space in visual memory. *Vision Research*, *41*(3), 329–41. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11164448

Shih, H.-T., Huang, W.-S., Liu, C.-H., Tsai, T.-C., Lu, C.-T., Lu, M.-K., … Lee, C.-C. (2007). Confusion or delirium in patients with posterior cerebral arterial infarction. *Acta Neurologica Taiwanica*, *16*(3), 136–42. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17966952

Smith, A. T., Singh, K. D., Williams, A. L., & Greenlee, M. W. (2001). Estimating Receptive Field Size from fMRI Data in Human Striate and Extrastriate Visual Cortex. *Cerebral Cortex*, *11*(12), 1182–1190. http://doi.org/10.1093/cercor/11.12.1182

Smyrnis, N., d'Avossa, G., Theleritis, C., Mantas, A., Ozcan, A., & Evdokimidis, I. (2005). Parallel processing of spatial and serial order information before moving to a remembered target. *Journal of Neurophysiology*, *93*(6), 3703–8. http://doi.org/10.1152/jn.00972.2004

Squire, L. R., & Zola-Morgan, S. (1991). The medial temporal lobe memory system. *Science*, *253*(5026), 1380–1386. http://doi.org/10.1126/science.1896849

Staresina, B. P., Duncan, K. D., & Davachi, L. (2011). Perirhinal and parahippocampal cortices differentially contribute to later recollection of object- and scene-related event details. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *31*(24), 8739–47. http://doi.org/10.1523/JNEUROSCI.4978-10.2011

Stoica, P., & Moses, R. L. (1990). On biased estimators and the unbiased {Cramer-Rao} lower bound. *Signal Processing*, *21*(4), 349–350.

Suzuki, W. A. (1996). Neuroanatomy of the monkey entorhinal, perirhinal and parahippocampal cortices: Organization of cortical inputs and interconnections with amygdala and striatum. *Seminars in Neuroscience*, *8*(1), 3–12. http://doi.org/10.1006/smns.1996.0002

Talamini, L. M., Nieuwenhuis, I. L. C., Takashima, A., & Jensen, O. (2008). Sleep directly following learning benefits consolidation of spatial associative memory. *Learning & Memory*, *15*(4), 233–237. http://doi.org/10.1101/lm.771608

Tibber, M. S., Anderson, E. J., Bobin, T., Carlin, P., Shergill, S. S., Dakin, S. C., … Foxe, J. (2015). Local and Global Limits on Visual Processing in Schizophrenia. *PLOS ONE*, *10*(2), e0117951. http://doi.org/10.1371/journal.pone.0117951

Todd, J. J., & Marois, R. (2004). Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature*, *428*(6984), 751–754. http://doi.org/10.1038/nature02466

Todd, J. J., & Marois, R. (2005). Posterior parietal cortex activity predicts individual differences in visual short-term memory capacity. *Cognitive, Affective & Behavioral Neuroscience*, *5*(2), 144–155.

Treisman, A. (1998). Feature binding, attention and object perception. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *353*(1373), 1295–306. http://doi.org/10.1098/rstb.1998.0284

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136. http://doi.org/10.1016/0010-0285(80)90005-5

Troiani, V., Stigliani, A., Smith, M. E., & Epstein, R. A. (2014). Multiple object properties drive scene-selective regions. *Cerebral Cortex*, *24*(4), 883–897. http://doi.org/10.1093/cercor/bhs364

Ungerleider, L. G., Courtney, S. M., & Haxby, J. V. (1998). A neural system for human visual working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *95*(3), 883–90. http://doi.org/10.1073/pnas.95.3.883

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*(6984), 748–51. http://doi.org/10.1038/nature02447

Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature*, *438*(7067), 500–3. http://doi.org/10.1038/nature04171

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology Human Perception and Performance*, *27*(1), 92–114. http://doi.org/10.1037//0096-1523.27.1.92

von Bastian, C. C., & Oberauer, K. (2013). Effects and mechanisms of working memory training: a review. *Psychological Research*, pp. 1–18. http://doi.org/10.1007/s00426-013-0524-6

Wager, T. D., & Smith, E. E. (2003). Neuroimaging studies of working memory: a meta-analysis. *Cognitive, Affective & Behavioral Neuroscience*, *3*(4), 255–74. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15040547

Wagner, U., Gais, S., & Born, J. (2001). Emotional memory formation is enhanced across sleep intervals with high amounts of rapid eye movement sleep. *Learning & Memory (Cold Spring Harbor, N.Y.)*, *8*(2), 112–9. http://doi.org/10.1101/lm.36801

Warren, D. E., Duff, M. C., Jensen, U., Tranel, D., & Cohen, N. J. (2012). Hiding in plain view: Lesions of the medial temporal lobe impair online representation. *Hippocampus*, *22*(7), 1577–1588. http://doi.org/10.1002/hipo.21000

Waters, G. S., & Caplan, D. (2003). The reliability and stability of verbal working memory measures. *Behavior Research Methods, Instruments, & Computers : A Journal of the Psychonomic Society, Inc*, *35*(4), 550–564. http://doi.org/10.3758/BF03195534

Wechsler, D. (1999). *Wechsler abbreviated scale of intelligence*. San Antonio: Pearson Education. http://doi.org/10.1177/0734282912467756

Wechsler, D. (2008). *Wechsler adult intelligence scale - Fourth Edition (WAIS-IV)* (IV). San Antonio: Pearson Education.

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General*, *131*(1), 48–64. http://doi.org/10.1037//0096-3445.131.1.48

Williams, D. L., Goldstein, G., & Minshew, N. J. (2006). The profile of memory function in children with autism. *Neuropsychology*, *20*(1), 21–9. http://doi.org/10.1037/0894-4105.20.1.21

Wilson, M. A., & McNaughton, B. L. (1994). Reactivation of hippocampal ensemble memories during sleep. *Science (New York, N.Y.)*, *265*(5172), 676–9. http://doi.org/10.1126/science.8036517

Winters, B. D., Forwood, S. E., Cowell, R. A., Saksida, L. M., & Bussey, T. J. (2004). Double dissociation between the effects of peri-postrhinal cortex and hippocampal lesions on tests of object recognition and spatial memory: heterogeneity of function within the temporal lobe. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *24*(26), 5901–8. http://doi.org/10.1523/JNEUROSCI.1346-04.2004

Woodman, G. F., & Chun, M. M. (2006). The role of working memory and long-term memory in visual search. *Visual Cognition*, *14*(4-8), 808–830. http://doi.org/10.1080/13506280500197397

Yates, F. A. (1992). *The art of memory*. London: Pimlico.

Yonelinas, A. P. (2013). The hippocampus supports high-resolution binding in the service of perception, working memory and long-term memory. *Behavioural Brain Research*, *254*, 34–44. http://doi.org/10.1016/j.bbr.2013.05.030

Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature*, *453*(7192), 233–5. http://doi.org/10.1038/nature06860

Zola-Morgan, S., Squire, L. R., Amaralt, D. G., Le Clair, C., & Micheletti, C. (1986). Human Amnesia and the Medial Temporal Region: Enduring Memory Impairment Following a Bilateral Lesion Limited to Field CA1 of the Hippocampus. *The Journal of Neurosci Ence*, (October), 2950–2967. http://doi.org/10.1093/neucas/2.4.259-aw

Appendix 1: Screening questionnaire

Please read carefully and answer the following questions.

Note: In case you do not feel comfortable in answering any question, please leave the space provided for that question open. Please feel free to ask for any clarifications, as you deem necessary.

1. Have you ever had or presently have any medical/neurological illness? (If yes, details):

   ____

   ____

2. Have you ever suffered from head trauma? (If yes, details):

   ____

   ____

3. Have you ever had or presently have any psychiatric illness? (If yes, details):

   ____

   ____

4. Have you ever been or presently are on medications? (If yes, details):

   ____

   ____

5. Have you ever been or presently are using any substance/drug (including nicotine and caffeine)? (If yes, details like number of cigarettes per day, etc.):

   ____

   ____

6. Have you ever had or presently have any family member having a medical/neurological or psychiatric illness? (If yes, details):

   ____

   ____

7. Have you participated in any other experiment/study in the past fortnight? (If yes, details like nature of experiment, any intervention used like TMS, beginning and end dates, etc.):

   ____

____

8. Are you participating in any other experiment/study at the moment/in the coming fortnight? (If yes, details like nature of experiment, any intervention used like TMS, beginning and end dates, etc.):

   ____

   ____

Thank you.

Appendix 2: Sleep Disorders Questionnaire

1. Have you been diagnosed with a sleep disorder, currently or in the past?

2. Have you been seen by a sleep specialist? If so, details?

Please read the statements carefully and encircle the score that best describes you.

Scoring Key: 1 Never 2 Rarely 3 Sometimes 4 Usually 5 Always

		Your score				
1	How often do you sleep well at night?					
2	How often do you have difficulty falling asleep?					
3	How often do you have difficult maintaining sleep?					
4	How often do you get up too early in the morning and find it difficult to go back to sleep?					
5	How often do you have difficulty staying awake during the day?					
6	How often do you experience sudden sleep attacks that are so intense that you must stop what you are doing to take a nap?					
7	How often do you nap during the day?					
8	How often do you sleep walk?					
9	How often did you sleep walk as a child?					
10	How often do you sleep talk?					
11	How often did you sleep talk as a child?					
12	How often do you have frightening dreams or nightmares?					
13	How often do you act out your dreams?					

14	How often do you move so much in your sleep that you accidently hurt yourself or your bed partner?					
15	How often do you experience persistent and uncomfortable feelings in your legs while sitting or lying down?					
16	How often do you experience persistent urge or need to move your legs while sitting or lying down?					
17	How often do you experience muscle twitches during your sleep or does your bed partner say that your muscles twitch?					
18	How often do you kick your legs during your sleep or does your bed partner say you kick your legs?					
19	How often do you snore or does your bed partner says that you snore?					
20	How often, according to you or your bed partner, do you gasp, choke, make snorting sounds, or stop breathing during your sleep?					
21	How often do you imagine feeling/seeing/hearing unusual and/or frightening people, animals, or objects, when you are falling asleep, during sleep, or waking up?					
22	How often do you find that you are unable to move when falling asleep, during sleep or waking up?					
23	How often do you experience episodes of muscle weakness in your legs or buckling of knees when you are emotionally charged (laughing, crying, angry, etc.), exercising, or after exercise?					
24	How often do you have palpitations or chest pain while sleeping?					

Appendix 3: Sleep Diary

		Average day	Day before testing	Testing day
1	What time did you go to bed?			
2	After settling down, how long did it take you to fall asleep?			
3	After falling asleep, how many times did you wake up in the night?			
4	After falling asleep, for how long where you awake during the night in total?			
5	At what time did you finally wake up?			
6	At what time did you get up?			
7	How long did you spend in the bed last night (from first getting into and finally getting up)?			
8	Ho long did you sleep last night [calculate by taking out the time you were awake in bed (including the time it took to fall asleep, item 2; awakenings during night, item 4; and morning, difference between items 5 & 6) from item 7]			
9	How would you rate the quality of your sleep? 1 2 3 4 5 very poor very good			

10	Considering your preferences, at what time would you ideally like to go to sleep?			
11	Considering your preferences, at what time would you ideally like to wake up?			