CHAPTER THREE

The Visual World in Sight and Mind: How Attention and Memory Interact to Determine Visual Experience

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Contents

Abstract

In this chapter, we describe how attention and memory interact to determine the extent and quality of our visual interactions with the world. We begin by considering the ways in which attention acts as a gatekeeper to visually-based memory. We then review the role attention plays in the maintenance of visual information in both short-term (working) and long-term memory. Finally, we describe examples of tasks and situations in which the contents

Psychology of Learning and Motivation, Volume 57
ISSN 0079-7421, DOI: 10.1016/B978-0-12-394293-7.00003-0

of visual memory reciprocally affect the guidance of attention through visual displays.

1. Introduction

The complexity and scope of the visual environments in which we live and work force us to shift our attention by moving our gaze and bodies from place to place, both to new locations and to previously visited ones, as we investigate our visual surroundings. Because of these movements, we do not necessarily (or often!) maintain perceptual access to all momentarily relevant aspects of the environment. To compensate, we accumulate and store visual knowledge in a multi-component memory system that provides us with access to information confronted in the past. This chapter examines the interplay between the attention and memory systems as we process our visual surroundings. Specifically, the focus is on the role of attention in determining the contents of visual memory, and, reciprocally, the role of visual memory in controlling attention during perceptually guided tasks. Prior to discussing these interactions, it is profitable to briefly highlight the general properties of the attention, visual working memory, and visual long-term memory systems.

1.1. Visual Attention

Since the advent of scientific psychology, attention has held a major place in theoretical discourses pertaining to human behavior. Informed by both introspection and experimentation, both Wilhelm Wundt's *Introduction to Psychology* (1912) and William James' *Principles of Psychology* (1890) devoted entire chapters to the discussion and interpretation of attention, addressing seemingly "modern" questions concerning the avenues through which attention is controlled, the limits of attentional capacity, the consequences of inattention, and the role of attention in cognitive processes such as perception, memory, and action planning. Across these discussions both Wundt and James characterize attention as a selective mechanism that limits processing to an appropriate subset of available objects or ideas, with the outputs of this selection determining one's experience of the world. As James put it:

> Millions of items of the outward order are present to my senses which never properly enter into my experience. Why? Because they have no interest for me. My experience is what I agree to attend to. Only those items which I notice shape my mind. Without selective interest experience is an utter chaos.

Today, the study of visual attention has been divided into a host of separable literatures: Reflexive, volitional, divided, covert, overt, space-based, object-based, and so forth, but the issue of selection pervades them all. Although details vary, every major theoretical conceptualization of attention has included some mechanism that constrains access to conscious awareness to a small subset of the information that is received by our senses. Filter-based theories (e.g., Broadbent, 1958; Deutsch & Deutsch, 1963; Treisman, 1964) propose a limited-capacity channel that restricts the flow of information from high capacity perceptual processes to low capacity short term memory processes. Race models (e.g., Bundesen, Shibuya, & Larsen, 1985) propose that all stimuli are processed in parallel, with selection occurring for those items that finish processing first. Biased competition accounts (e.g., Bundesen, 1990; Desimone & Duncan, 1995) argue that stimuli compete for entry into awareness with the winner determined by a combination of perceptual biases and cognitive goals. Connectionist models (e.g., Deco & Zihl, 2001; Heinke & Humphreys, 2003; Humphreys & Muller, 1993; Mozer, 1991; Phaf, Van der Heijden, & Hudson, 1990) propose that selection is achieved through combinations of activation and inhibition that spread through a series of feature maps that encode the visual display. Spotlight and zoom-lens models (e.g., Eriksen & Yeh, 1985; Eriksen & St. James, 1986; Posner, 1980) view attention as a singular attentional field applied to a region of space within which stimuli are granted access to awareness. For purposes of this chapter, the relative merits of these specific theories of attentional control are of minor interest and have been reviewed elsewhere (e.g., Bundesen & Habekost, 2008). What is most relevant for our discussion is the fact that selection mechanisms are of paramount importance in any conceptualization of attention and, because they determine the amount of processing devoted to a stimulus, serve as a kind of keystone against which human experience is built. Here, we will consider how selection, once achieved, influences one's visual representation of the environment and determines his or her visually-guided behaviors.

1.2. Visual Working Memory

To be consciously aware of some aspect of the visual world is to store that component of the environment in visual working memory (VWM). The preceding section equated awareness with the outcome of selective attention processes, and so, by substitution of terminology, we can view selective attention as the gateway to VWM representation. The purpose of VWM is to enable the short-term (several seconds) retention and manipulation of information in the service of immediate action. Because access to VWM is controlled by selective attention it should come as no surprise that it is subject to inherent limitations. Chief among these is a limited storage capacity, the source of which has been the focus of intense research.

Canonically, the capacity of VWM is 3–4 items (e.g., Cowan, 2000; Irwin & Andrews, 1996; Luck & Vogel, 1997), which is a very small subset of the items that could be stored. Initial conceptualizations of VWM capacity considered this limit to be inflexible, owing to a slot-like system that assigned one object to one slot, with a maximum of 3–4 slots available (Luck & Vogel, 1997). Under this view, individual items are represented in an all-or-none fashion, with a whole object entered into or lost from a slot. There is now a general agreement that such an account is too simplistic although there remains no clear consensus regarding the source of VWM capacity limits. One of the chief problems with fixed-slot models is that the number of objects that can be stored in VWM varies according to the nature of the to-be-remembered stimuli. For example, fewer complex three-dimensional polygons and unfamiliar faces can be remembered than simple two-dimensional shapes or color patches (Alvarez & Cavanagh, 2004; Olsson & Poom, 2005). *Fixed-resource theories* (e.g., Barton, Ester, & Awh, 2009; Zhang & Luck, 2009) account for these findings by reconceptualizing VWM as a series of slots over which observers can flexibly allocate information. For example, a complex object may occupy two slots while simple objects may be accommodated within a single slot. Once the available slots are filled, however, capacity has been reached and no further information can be stored. Another class of theories abandons the notion of slots altogether and instead argues that VWM capacity is limited by the availability of processing resources. Under this *flexible-resource* view, the maintenance of an object in VWM requires some amount of cognitive effort and applying this effort depletes the resource pool. A tradeoff then exists between the number of objects remembered and the amount of resources available to support their representation: an observer can maintain a few precisely-represented objects before resources run out, or relatively more less-precisely encoded objects (Bays & Husain, 2008; Bays, Catalao, & Husain, 2009; Wilken & Ma, 2004). Once again, our purpose here is not to weigh the relative merits of these theories of VWM capacity (see Fukuda, Awh, & Vogel, 2010 for such a discussion), but is instead to appreciate the fact that VWM is capacity limited and that some mechanism(s) must control the access to and maintenance of VWM. Here, we will consider the role attention plays in this process, as well as the influence the contents of VWM have on future selection.

1.3. Visual Long-Term Memory

Visual experience extends well beyond the temporal dimensions of VWM. Visual long-term memory (VLTM) maintains visual information in a relatively permanent store. Functions such as object identification, scene recognition, visual search, and navigation depend on VLTM (see Hollingworth, 2009 for review). Hence, after visual information is no longer required in working memory, there is cause to, at times, retain this information in a longer-term store. In contrast to VWM, visual long-term memory is remarkably bountiful and precise. People are able to explicitly recognize thousands of novel scene images after a single exposure to them (Standing, 1973). What is more, a single 5-s viewing period is sufficient to produce above-chance memory for a photograph after a 1-year delay (Nickerson, 1968). These long-term memories include global scene structure and object position information as observers are able to accurately discriminate images they saw from mirror reversed lures in which the gist remains the same while visual details change (Standing, Sell, Boss, & Haber, 1970). Such impressive memory is not limited to overall recognition of scenes, however, as it also extends to the details of individual objects within scenes. For example, after viewing hundreds of objects in dozens of scenes, observers are able to discriminate depictions of objects they saw from foils drawn from the same semantic category and can detect small changes in object details such as their orientation (Hollingworth, 2004). More compelling still is the fact that these abilities do not require intentional memorization of the scene on the part of the observer (Williams, Henderson, & Zacks, 2005). In this chapter we will consider how such remarkably detailed long-term memory representations can be profitably used to influence the guidance of attention through the visual world.

2. Attention and the Encoding of Information in Visual Working Memory

Since Sperling's work in the 1960s, researchers have known that attention-directing cues such as arrows and spatially localized tones can influence which items are encoded into VWM if the cues appear either before stimulus offset or before the iconic image of the stimulus has faded (e.g., Averbach & Coriell, 1961; Sperling, 1960). These findings have led researchers to argue that attention helps transfer important aspects of a perceptual display into VWM (see Schmidt, Vogel, Woodman, & Luck, 2002; Vogel, Woodman, & Luck, 2006). Here, we describe the role of attention in this process by highlighting three phenomena that have had a substantial impact on theoretical conceptualizations of this interplay: change blindness, the attentional blink, and just-in-time search strategies.

2.1. Change Detection and Change Blindness

The visual world is dynamic and ever-changing and appreciation of these changes can often be behaviorally relevant (see Figure 1). While standing on a street corner, an observer may witness drastic changes in the composition of a scene including the objects in view (e.g., specific people and cars) as well as the visual properties of objects (e.g., the color of the traffic lights, rate and direction of traffic flow, etc.). While some of these changes may be trivial to our hypothetical pedestrian, others must be appreciated in order for him or her to safely cross the street. The world's dynamic nature also means that our visual experience will not always meet our expectations or conform to our predictions. Drivers failing to stop at a red light are (fortunately) rare and unexpected but can clearly be important to one's health and well-being.

Fortunately, when perceptual contact with the visual world is continuous, attention mechanisms are tuned to detect many of the perceptual signals that occur as a result of sudden changes to a display. For example, attention is captured by local shifts in motion (e.g., Abrams & Christ, 2003; Franconeri & Simons, 2003), luminance (e.g., Irwin, Colcombe, Kramer, & Hahn, 2000), and color (e.g., Boot, Brockmole, & Simons, 2005; Matsukura, Brockmole, Boot, & Henderson, 2011). When visual changes are obscured by disruptions in visual input, however, these perceptual signals are lost, and the detection of changes depends on VWM. This dependency has made change detection tasks ubiquitous in the literature, with performance on them serving as a standard operational definition of VWM abilities.

Much of the work using change detection has focused on the failures of memory and visual awareness. Because VWM is sharply limited in capacity (see Section 1.2), changes that occur when perceptual contact with the world is lost are often left unnoticed. An everyday corollary to this problem can be found in "spot the difference" puzzles in which one is to identify the few differences between two otherwise identical pictures. As we look back and forth between the images, our eye movements serve to disrupt the continuity of vision (Matin, 1974; Volkmann, 1986; Zuber & Stark, 1966). As a result, the differences between the images are difficult to detect. In a dynamic world, the corresponding difficulty we have with noticing changes to scenes has been termed *change blindness*.

In controlled experiments, a variety of approaches have been used to demonstrate and evaluate the phenomenon of change blindness. The most common method has been to artificially occlude the observer's view of a scene during a change by using a "flicker" or strobe-like effect which is intended to simulate blinks or eye movements (e.g., Rensink, O'Regan, & Clark, 1997). Another approach has been to disrupt the continuity of visual input by occluding an observer's visual field in

Figure 1 Six photographs taken at the intersection of Forrest Road and Teviot Place in Edinburgh, Scotland within a 30 second window. While the visual world is globally stable, local aspects are in a constant state of flux leading to unique and dynamically changing perceptual events. (Brockmole, J. R., & Matsukura, M. (2011). Eye movements and change detection. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.). *Oxford Handbook of Eye Movements* (p. 563–578). New York: Oxford University Press. Used with permission by Oxford University Press.) (For color version of this figure, the reader is referred to the web version of this book.)

a more naturalistic way through the movement of objects (e.g., Simons & Levin, 1998) or a change in the observer's viewpoint (e.g., Levin & Simons, 1997). The third approach has been to introduce changes to a scene during a saccadic eye movement (e.g., Currie, McConkie, Carlson-Radvansky, & Irwin, 2000; Grimes, 1996; Henderson & Hollingworth, 1999; McConkie & Currie, 1996) so that saccadic suppression will serve as a naturally occurring, momentary, though subjectively imperceptible, disruption to visual input. In all three of these paradigms, the primary dependent variable is the rate (measured either in time required to localize a repeating change or the proportion of changes that are detected within a defined temporal window) with which the imposed changes are explicitly noticed by the observer. Each of these methodological approaches has unequivocally demonstrated that color alterations, object translations, object rotations, size scalings, object additions or deletions, and object token substitutions can be missed at surprising rates—even when vision is disrupted for only tens of milliseconds during the change (see Simons & Rensink, 2005 for a review). For example, in Grimes' (1996) study where changes occurred during saccades, 100% of observers failed to detect a one-fourth increase in the size of a building in a city skyline, 92% failed to detect a one-third reduction in a flock of 30 birds, 58% failed to detect a change in a model's swimsuit from bright pink to bright green, 50% failed to detect two cowboys exchange their heads, and 25% failed to notice a 180° rotation of Cinderella's Castle at Disneyland!

The importance of change detection tasks, however, does not lie in their value as parlour tricks, but in their value as a means to explore the manner in which information is entered into and maintained in VWM. To detect a change across a visual disruption, the current perceptual episode must be compared to previous perceptual episodes stored in VWM. If a mismatch can be found, change detection is trivial; if not, change detection will fail. So, what factor(s) would make it more or less likely that an object will be stored in VWM? In the following paragraphs, we will see that the factors that influence the allocation of selective attention predict rates of change blindness very well.

When viewing a scene, not all areas or objects will be attended. Indeed, during any viewing episode, observers shift their gaze (i.e., overt attention) from place to place, as high-resolution details are obtained from relatively local aspects of the scene surrounding the point of fixation. Factors such as stimulus salience (e.g., Itti & Koch, 2000), an observer's prior experience (Brockmole & Henderson, 2006b), and an observer's goals (e.g., Hayhoe, 2000) interact to determine the areas an observer chooses to look at, and those he or she decides to forgo (e.g., Torralba, Oliva, Castelhano, & Henderson, 2006). To the extent that attention controls access to VWM, this non-uniform allocation of attention to a display should result in an equally non-uniform ability to detect changes to all objects or features. This hypothesized importance of selective attention to an observer's ability to realize changes in a visual environment has been demonstrated in several ways.

One of the first approaches to linking attention and change detection was to manipulate the subjective importance of the changes taking place in a scene. For example, Rensink et al. (1997) asked observers to detect changes in a flicker paradigm where 80 ms gray screens were inserted between 240 ms scene presentations. Changes were made to either objects of high or low interest to the observers, as defined by verbal descriptions of the scenes (i.e., areas that were included in scene descriptions more frequently were scored as being more interesting). Their results showed that changes to objects of central interest were detected more quickly than changes to objects of marginal interest, a finding the researchers explained by arguing that subjectively important scene regions are preferentially attended.

While a variety of other explanations for Rensink et al.'s findings are possible, converging evidence for their conclusions was obtained by Hollingworth and Henderson (2000), who considered change detection rates for objects that appeared in either expected or unexpected contexts. For example, a fire hydrant could appear within a street scene or a living room scene. The elegance of this design is that multiple visual factors are controlled (the fire hydrant is visually identical in both situations) while semantic information is varied. Because the information carried by objects placed in consistent scenes is redundant with that portrayed by other objects in the scene, but new, non-redundant information is provided by inconsistent objects, semantic inconsistencies are considered to be more informative. As a result, inconsistent objects receive some degree of attentional prioritization during scene viewing (Brockmole & Henderson, 2008; Gordon, 2004; Henderson & Hollingworth, 1998). Indeed, Hollingworth and Henderson's results showed that change detection is improved when changes are made to the semantically informative objects.

Rather than correlating change detection abilities to the various types of information within a scene (e.g., importance or meaningfulness), another approach to linking selective attention and working memory has been to monitor eye movements and to then compare change detection rates of objects that were viewed and those that were not. Because attention and gaze are tightly coupled (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Irwin & Gordon, 1998; Kowler, Anderson, Dosher, & Blaser, 1995; Shepherd, Findlay, & Hockey, 1986), eye movements are a direct measure of attention allocation. Taking advantage of this fact, Hollingworth and Henderson (2002) showed that while changes to objects that have not yet been fixated are poorly detected (in fact, correct detections did not exceed false alarms), changes to objects that have been fixated are noticed at rates up to five times greater than false alarms (see also Grimes, 1996). Similarly, the accuracy of change detection is correlated with the distance between the scene change and the position of gaze immediately prior to the change (Grimes, 1996; Henderson & Hollingworth, 1999).

A last approach we will describe that has linked attention and VWM using change detection tasks has been to correlate enhancements in a viewer's own attentional resources with improved VWM. According to the embodied approach to cognition, how one uses his or her body in the world is one such way to manipulate attentional resources. For example, the visual space around the body is known to receive attentional prioritization compared to space far from the body (Reed, Grubb, & Steele, 2006; Reed, Betz, Garza, & Roberts, 2010) and intentionally bringing an object into one's body space, such as by taking it into the hands, can be a means for engaging more attentional resources to devote toward that object. In support of this, Abrams, Davoli, Du, Knapp, and Paull (2008) showed that holding the hands around a visual display led to prolonged attentional processing of items in that display. As such, one could predict that hand proximity to an object or display should have implications for VWM: if VWM is reliant upon attention, and attentional resources are enhanced for objects in the hands, then VWM should be improved by holding to-be-remembered objects in the hands. Tseng and Bridgeman (2011) investigated this possibility using a one-shot, single-flicker change detection paradigm. On each trial an initial display of 8 or 12 colored squares was briefly presented for 200 ms and, after a 900 ms blank interval, the display returned either with one square having changed color or with no change to any of the squares. Participants were simply asked to indicate whether or not they had noticed a change on each trial. Critically, participants performed the task while holding their hands either in their laps (thus far from the display) or alongside (thus near to) the visual display. Indeed, holding the display in the hands improved one's sensitivity for detecting changes, increasing the capacity of VWM by approximately .6 and .75 objects on 8- and 12-object displays, respectively.

In addition to holding an object in the hands, another way in which the body may be used to manipulate attention is to prepare to act upon an object. It is well-established that the preparation of an action can reflexively reorient attention to the space of the to-be-performed action, as attention is necessary to efficiently and effectively guide an action to a spatially localized target (e.g., Castiello & Paine, 2002; Rafal, Calabresi, Brennan, & Sciolto, 1989; Rizzolatti, Riggio, Dascola, Umiltá, 1987; Tipper, Lortie, & Baylis, 1992). Using similar logic to that laid out for hand proximity, if the preparation of an action, such as a reach-and-point motion, can reallocate attention to a target object, then VWM for that object might also be improved. Tseng et al. (2010) tested this possibility using an implicit change detection paradigm in which a single 100 ms flicker was inserted between 500 ms presentations of slightly different versions of the same natural scene. Although none of the differences presented in this manner could be consciously identified, participants nevertheless were able to perform above chance levels. Moreover, participants who pointed to and touched on-screen where they thought the change was outperformed those who simply responded verbally.

To summarize this section, change blindness results when perceptual contact with an environment is lost during the moment of the change. As a result, these changes are not directly perceived and recognition of the change requires a VWM representation of an objects pre-change state. The likelihood that such a representation exists depends on several factors known to influence the allocation of visual attention. Objects that are subjectively important to a scene or that carry heightened semantic informativeness receive a disproportionate amount of attentional processing and, as a result, are better represented in VWM and are more immune to change blindness. In addition, objects that have been recently attended or that are nearby the current locus of attention are more likely to be represented in VWM and, similarly, to show reduced susceptibility to change blindness. Finally, objects and scenes that are within hand-space, or that constitute the end-point of an action, receive attentional prioritization that in turn leads to better VWM and hence better change detection. Preparing to interact with an object or taking an object into the hands may therefore be a means for improving performance on memory-dependent tasks. From this collective body of evidence, then, one can conclude that attention mechanisms play a major role in determining which aspects of an environment will be represented in VWM. Despite the dominating role change detection tasks have played in VWM research, other approaches have provided additional important insights into the relationship between attention and working memory. We turn to some of these next.

2.2. The Attention Blink

The dynamic nature of the visual world means that an observer is exposed to an ever-changing stream of visual information. Information that may be present at one moment may be gone the next. In such situations, the temporal dynamics of attentional allocation are important determinants of processing. If the world changes faster than attention can be allocated among objects of interest, then performance on a wide range of tasks can suffer. There have been several approaches to determining the temporal aspects of selection (for examples of other approaches not discussed here, see Carlson, Hogandoorn, & Verstraten, 2006; Chakravarthi & Van Rullen, 2011; Ibos, Duhamel, Hamed, 2009; Sperling & Weichselgartner, 1995; Theeuwes, Godign, & Pratt, 2004; Wolfe, Alvarez, & Horowitz, 2000; and Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004), but perhaps none has inspired more research (and debate) than the *attention blink (AB).*

The AB refers to an effect observed when observers are monitoring a rapid serial visual presentation (RSVP) of stimuli for the presence of two or more pre-defined targets. Typically, accuracy for identifying the first target to appear (T1) is nearly perfect. However, identification of a second target (T2) is typically reduced if it trails the first by 200–500 ms (e.g., Broadbent & Broadbent, 1987; Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992; Weichselgartner & Sperling, 1987; see Martens & Wyble, 2010 for a recent review). Colloquially speaking, it seems as though attention "sticks" to the processing of T1 for some time after its physical disappearance and because of this, attention is unable to be reallocated to the processing of subsequent visual stimuli. This short-lived "blink" is resolved within 500 ms, after which an observer's ability to detect T2 is restored.

Broadly speaking, researchers agree that the AB reveals a limitation on the control of selective attention and that this limitation has consequences for one's ability to encode information in VWM. What is contentious about the AB, however, is the exact mechanistic cause for this bottleneck. The primary question in this conversation has revolved around the level of processing at which the blink occurs. One possibility is that the AB reflects a loss of sensory data. This appears to not be the case. For example, studies have shown Event Related Potential (ERP) components linked to the early registration of perceptual stimuli (P1 and N1) are normally evoked by an attentionally blinked stimulus (Vogel, Luck & Shapiro, 1998). Hence, the AB seems to reflect a post-perceptual limitation. Given the lack of awareness observers have for T2, one can ask if the AB reflects a complete lack of post-perceptual processing. This also appears to not be true. Both behavioral and neuroimaging studies have demonstrated that despite the loss of explicit awareness of T2, it nevertheless gives rise to semantic processing. Behaviorally, when using words as stimuli, a missed T2 facilitates the processing of related words presented afterward (Martens, Wolters, van Raamsdonk, 2002; Shapiro, Driver, Ward, & Sorensen, 1997). Neurologically, ERP components associated with semantic processing (such as the N400) are equivalent for T1 and T2 items suggesting that during the AB, semantic processing continues normally. What kind of mechanism can allow for normal perceptual processing of an item, normal semantic processing of an item, but an acute lack of awareness for that item? One possibility is that the AB compromises the encoding of information in VWM for retention. Should this occur, at the conclusion of a trial, T2 would not be reportable, despite the fact that it was perceived and processed. Direct evidence for this interpretation was obtained by Vogel et al. (1998) who showed that the P3 ERP component, one that is strongly linked to the updating of VWM (Donchin, 1981) is completely suppressed during the AB. This provides strong evidence that the AB reflects a post-perceptual attentional bottleneck that restricts access to VWM.

In addition to determining the mechanism by which the AB arises, one can ask if there is any remedy for the AB or whether it reflects a fundamental and inflexible limitation on attention allocation. Initially, it seemed that the AB was insoluble. This conclusion was based on studies that showed that despite extensive practice and training, the AB cannot be eliminated (e.g., Braun, 1998; Maki & Padmanabhan, 1994). Later research, however, would show that the AB is not immune to various attentional manipulations. It is rare that dual-task situations benefit cognitive processing, but this seems to be the case with the AB. For example, asking observers to listen to music or to recall a vacation seems to alleviate the AB (Olivers & Nieuwenhuis, 2005, but see Olivers & Nieuwenhuis, 2006) as does distraction by irrelevant visual motion (Arend, Johnston, & Shapiro, 2006) and switching between various goals (Ferlazzo, Lucido, Di Nocera, Fagioli, & Sdoia, 2007). Collectively, these manipulations reduce the amount of attention allocated to T1 and in return, the free attention resources are available to process T2. The validity of this remedy is further supported by evidence for the converse: increasing attentional allocation to T1 by inserting an emotionally arousing word for T1 (Mathewson, Arnell, & Mansfield, 2008) or by presenting T1 near the hands (Abrams et al., 2008) results in a more pronounced attentional blink. Other tradeoffs between T1 and T2 processing can also be observed that both augment and complicate the picture presented in this short review (e.g., Dell'Acqua, Jolicoeur, Luria, & Pluchino, 2009; Dux, Asplund, & Marois, 2009; Dux & Marois, 2009; Giesbrecht, Sy, & Lewis, 2009; Martens & Johnson, 2005, 2008; Nieuwenstein, Chun, van der Lubbe, & Hooge, 2005; Nieuwenstein & Potter, 2006; Olivers & Meeter, 2008; Potter, Nieuwenstein, & Strohminger, 2008; Seiffert & Di Lollo, 1997), but for our purposes we've said enough to make the point that while the AB demonstrates a strong link between attention and access to VWM, it does not seem to imply a hard-wired or inflexible bottleneck within working memory. As with change blindness, then, evidence derived from the AB paradigm indicates that attention mechanisms play a major role in determining which aspects of an environment will attain access to VWM and conscious awareness.

2.3. Just-in-Time Strategies

The strategies that an actor employs when completing a perceptually guided task also suggest that attention acts as a gatekeeper for VWM.

When performing any real-world task, only certain information is relevant to each action the actor must make. For example, when making a peanut butter and jelly sandwich, an actor must, at some point, pick up the jar of peanut butter. The information that is necessary to complete this task includes the location, size and orientation of the jar, while color information is likely irrelevant. When discriminating peanut butter from jelly, however, color information may be useful while orientation may not. Thus, the task-relevant features of an object are constantly in flux. Several lines of research suggest that when executing these various natural actions observers adopt a *just-in-time strategy* where fixations are made for the purpose of obtaining only the specific information that is immediately relevant to their next action. What consequence would such an acquisition strategy have on memory? Given discussion in previous sections, we should predict that the momentary contents of VWM will reflect the momentary needs of the observer, and no more. As such, the momentarily irrelevant features of an object will not be maintained in VWM while task-relevant information is only held in memory as long as necessary to complete some sub-task. We review some of this evidence here.

Ballard, Hayhoe, and Pelz (1995) initially described the just-in-time strategy in a model replicating task. Participants were given a model constructed of colored blocks and were instructed to replicate the model with a second set of blocks. To complete this task, participants generally fixated a block in the model, moved their eyes to guide the pick-up of a corresponding block, but then, before positioning the block in their reconstruction, observers again fixated the model. This pattern of fixations suggests that the participants first fixated the model to obtain color information about the block they should pick up and then fixated the model again to obtain spatial information about where that block should be placed. In this way, participants attended to the feature information they needed only at the precise moment that they needed it instead of attending to both task-relevant features of the object at the same time (see also Droll & Hayhoe, 2007; Gajewski & Henderson, 2005; Hayhoe, Bensinger, & Ballard, 1998; Land & Hayhoe, 2001; Triesch, Ballard, Hayhoe, & Sullivan, 2003).

Another set of studies has used change detection as a means to examine the consequences of just-in-time strategies on VWM representations. Hayhoe, Bensinger, and Ballard (1998) demonstrated that manipulations of a model display like that used by Ballard and colleagues often went unnoticed while participants completed the reconstruction task. More surprisingly, Triesch et al. (2003) found that participants often failed to notice changes in the traits of the object they were actively manipulating if those changes were made to features not momentarily relevant! In Triesch and colleagues' study, subjects were presented with tall and short blocks that they were asked to place on one of two conveyor belts in a virtual environment. The instructions given to subjects were manipulated so that the height of the blocks was task-relevant at different times during a trial. In different conditions, height was either irrelevant to their task, relevant only to their decision of which block to pick up next, or relevant to both their choice of which block to pick up and to their choice of which conveyor belt to place that block on. On some trials, the height of the block was switched from tall to short (or vice versa) while the participant was moving it to the conveyor belt. Participants were instructed to report any size changes that they noticed. In the first condition, when the height of the block was never task relevant, participants were least likely to notice the changes in block size. In the second condition, when the height of the block was only relevant at the beginning of the trial, participants noticed relatively more changes. Participants in the third condition, when the height of the block was relevant throughout the trial, noticed the most changes of the three groups (although they did not detect all of them). These results indicate that the timing of the change is key—as long as the feature change occurs when the feature is momentarily task-relevant, the likelihood of its detection is high. If, however, a change occurs when the feature is no longer task-relevant, it will most likely not be detected. A similar study, conducted by Droll, Hayhoe, Triesch, and Sullivan (2005), found that changes to a manipulated object likely went unnoticed due to a failure to update the representation of that feature in VWM, perhaps due to a failure to re-attend that feature once it ceased to be task-relevant. These findings together further suggest that just the task-relevant feature of an object is attended and encoded into VWM, and that this representation is maintained only long enough to meet task demands. Hence, as with studies of change detection (Section 2.1.) and target identification (Section 2.2.), results of this kind suggest that focused attention may be necessary before an object (or a subset of its specific component features) is encoded into VWM.

3. Attention and the Maintenance of Information in Visual Working Memory

Moving on from issues of encoding, let's now consider issues of storage. Given its limited duration and capacity, the contents of VWM must be constantly updated or "refreshed." Here we present some evidence that attention plays a role (although not a solitary one) in determining the capacity and contents of VWM.

3.1. Attention and VWM Capacity

How much information can be retained in VWM at a given moment? The canonical answer to this question is 3–4 items, although various factors can increase or decrease this limit somewhat (see Section 1.2). In this section, we present evidence that executive attention is one of these factors.

Vogel and Machizawa (2004) showed observers arrays of colored squares that were evenly split across the left and right sides of the display. On any particular trial, a directional cue informed observers which side of the display was to be remembered. After a short retention interval, a test array was presented that was either identical to the memory array or in which one square changed color. Observers were to indicate whether an item changed color or not. During each trial, the researchers recorded ERPs from electrode sites spanning the scalp. The main independent variable in this experiment was the number of objects present in the to-be-remembered array. One aspect of the ERP recordings proved to be particularly related to the number of objects committed to VWM. Specifically, a sustained negative ERP signal was recorded across the posterior parietal, lateral occipital, and posterior temporal electrode sites in the hemisphere contralateral to the remembered hemifield. This *contralateral delay activity (CDA)* increased in magnitude as memory load increased, but reached an asymptotic magnitude when arrays were composed of three or more items, a value accepted as the canonical limit of VWM capacity. In fact, when correlating CDA magnitude with behavioral measures of VWM capacity on an individual-by-individual basis, Vogel and Machizawa found that the CDA accounts for over 60% of the variance in behaviorally observed memory capacity.

Having established that the CDA is a reliable brain-based measure of VWM capacity, Vogel, McCullough, and Machizawa (2005) used it as a means to relate VWM capacity to an observer's executive ability to selectively attend to task-relevant information. Their procedures were generally analogous to those described above, with arrays of objects split across the left and right hemifields. On any particular trial, observers were to remember either two or four objects. The key difference in this study was the inclusion of irrelevant objects in each hemifield. Hence, an observer may have to remember both objects in a two object display, two objects in a four item display, or all four objects in a four item display. In addition to measuring the CDA under these circumstances, Vogel et al. behaviorally measured each individual's VWM capacity and divided participants into high and low VWM capacity cohorts. For all individuals, the CDA increased as the to-be-remembered set size increased from two to four. However, important group differences emerged when irrelevant, to-be-ignored items appeared in the attended hemifield. For those in the high memory capacity group, the CDA magnitude when remembering two of four items was the same as when they were remembering two items in isolation. For those in the low capacity group, CDA in the two of four condition was equal to the case where all four objects were to be remembered. Hence, the number of objects that a particular individual can remember is directly related to his or her ability to vigilantly attend to task-relevant information and to ignore task-irrelevant information. Converging evidence for this conclusion has been obtained in anti-saccade paradigms where individuals of lower working memory capacity have a more difficult time looking way from a salient visual cue (Kane, Bleckley, Conway, & Engle, 2001). Additional relationships between executive attention and working memory capacity have been described in theories of working memory that extend beyond the visual domain, and hence beyond the scope of this chapter (see Unsworth & Engle, 2007). In Section 4.2, we will return to issues of working memory capacity when we describe ways in which an individual's capacity to store information reciprocally determines how well he or she can allocate attention to visual displays.

3.2. Attention and VWM Storage

The preceding discussion highlighted the important role attention plays in determining how much information an individual can retain in VWM. Next, we consider the role attention plays in the maintenance of information in VWM during a retention interval. From the early days of working memory research (when it was called short-term memory and primarily studied using verbal stimuli), it has been clear that the short-term maintenance of information requires control processes such as active rehearsal. If, during a retention interval, observers are also engaged in a difficult attention-demanding task such as counting backward from a random 3-digit number in multiples of three, they experience a decrease in the amount of information that they can retain in memory (Brown, 1959; Peterson & Peterson, 1959). Within the visual domain, similar results have been obtained. For example, Gajewski and Brockmole (2006) asked observers to remember an array of colored shapes. During the retention period, a sudden visual onset (a localized flash of light) appeared in a location previously containing one of the to-be-remembered items. This onset captured visual attention, and as a result, memory for items near the distracting event was better than that for objects further away. This suggests that a 'spotlight beam' of attention shifted and narrowed from all objects to just a few, leading to differential memory for objects in the display (see also Griffin & Nobre, 2003; Matsukura, Luck, & Vecera, 2007). The converse of this relationship between attention and memory also seems to hold. For example, items presented in locations that are maintained in spatial visual working memory are processed more quickly and more accurately than are items presented in spatial locations that are not actively retained in memory (Awh, Jonides, & Reuter-Lorenz, 1998). Like several of the studies presented in the previous section, this pattern of results suggests a bi-directional relationship between attention and VWM mechanisms.

In an effort to delve into this relationship further, researchers have recently been asking what mechanism might enable attentional cues to affect the storage of items in VWM once perceptual representations are gone. At least two possibilities have been considered. One possibility is that attention protects the representation of the cued item from degradation due to decay, interference, or some other source. As such, the resolution of the cued item remains strong during a retention interval making it ultimately more useful when engaging in some memory-demanding task. A second possibility is that attention could act to prioritize the order in which items in VWM are mentally accessed or interrogated. To perform many behaviors, items in memory must be compared to new items that come into view, and this process may be prone to errors. Attention could bias observers to begin their comparisons with the cued object (making it less error prone), and only after this comparison fails, other un-cued items in memory would be interrogated.

To distinguish these possibilities, Matsukura et al. (2007) developed a double-cuing change detection procedure. Observers were shown two arrays of objects separated by a brief delay interval and asked to report whether the two arrays were identical or different. In their paradigm, the memory array contained two sets of objects (left and right side of display). On most trials, a single arrow directed attention to one of these sets of objects. The observers' task was to report whether a probed set was the same as or different from its counterpart in the memory array. On a critical subset of trials, a second arrow was presented after the first (i.e., a double cue). Each arrow pointed to the same set of objects or to different sets of objects. Observers were told that if two arrows appeared, it would be the second one that would always predict which set of items would be tested. The protection account predicts that the first-cued set of objects would be protected from decay or interference while the other set of object would be subject to decay/interference. Thus, observers' memory should be more accurate when two arrows point to the same set of objects (i.e., the cued/prioritized objects are tested) than when they point to different sets of objects (i.e., the second cued/degraded objects are tested). However, the prioritization account predicts that the (100% valid) second-cued set should take priority in the comparison to the test items. Thus, observers' performance should be similar when the arrows point to the same set of objects or to different sets of objects. Results were unambiguous and the protection account was confirmed. Once attention was directed to one set of objects during the retention interval, the other set began to decay. A subsequent cue to the decaying set did not rescue performance. These experiments confirm that attentional cues can be used to protect already-formed VWM representations from degrading over time. Thus, shifts of attention to task-relevant aspects of a display after perceptual analysis can help preserve those aspects of VWM that are most relevant, ensuring that it is only the least relevant information that is replaced.

The role of attention in the maintenance of VWM representations has also been couched in terms of the *binding problem*. Briefly take a look at the display illustrated in Figure 2, then, look away and try to recreate the display either mentally or on a piece of paper. In order to do this accurately, you had to remember the precise combinations of features such as color, shape, and location. This task is challenging because visual processing acts much like a prism, splitting visual information from the retinal image into separately processed visual features. *Binding* refers to the set of neural and cognitive mechanisms that reintegrate these features to create a holistic representation of the objects in the visual field. In relation to VWM, there are two main issues to address (there are many more if we also consider binding mechanisms at lower and higher levels of cognition, see, for example, Brockmole and Franconeri, 2009). First, how does an observer represent the fact that features a, b, and c belong to object X, whereas features q, r, and s belong to object Y? Second, what happens to bound representations when the relations among features, objects, or events change? We will address these in turn by considering the role attention plays in the maintenance of bound object representations in VWM.

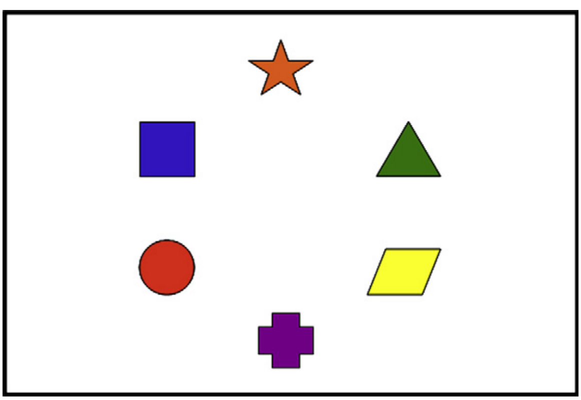

Figure 2 Accurate memory for displays like this requires one to bind color, shape, and location information in visual working memory. (For color version of this figure, the reader is referred to the web version of this book.)

Given much of our previous discussion, there seems to be little doubt that attention plays an important role in the maintenance of objects in VWM. Our question about the role of attention in binding is more nuanced and can perhaps be more accurately captured by asking whether objects defined by multiple features (i.e., requiring binding) require a level of attention over and above that needed for simple, single feature items. This question stems from prior work that developed Feature Integration Theory (FIT, Treisman & Gelade, 1980) which demonstrated that spatial attention is particularly important for the proper perception of feature conjunctions.

According to FIT, although individual visual features are detected relatively automatically, participants cannot know which of these features go together unless attention is focused on particular locations. Treisman and Gelade (1980) noted that directing attention to a point in space precedes the identification of information at that location. This leads to the conclusion that focusing attention on a particular spatial location then allows the features at that location to be bound together so that an item can be identified. Braet and Humphreys (2009) have linked this process to reentrant processes stemming from higher visual areas such as the Posterior Parietal Cortex (PPC) that feedback to early visual pathways. When transcranial magnetic stimulation (TMS) pulses are applied to the PPC 150–200 ms after the presentation of a binding task, the pulse disrupted binding performance. These data lend support to a multistage model of binding where attentional feedback, specifically from PPC, plays an important role in relatively late perceptual processes related to feature binding.

Following on from the evidence highlighted above, we can ask if attention is required to preserve feature bindings in VWM just as it is during the initial perception of multi-feature objects. Recently, Treisman (2006) argued that this may indeed be the case and generalized the tenets of FIT to VWM based on evidence emerging at the time which indicated that attention is required to maintain the bindings between features. Perhaps the first suggestion that attention is critical to maintaining bound object representations in VWM came from Wheeler and Treisman (2002) who showed that in many cases, remembering precise combinations of features is more difficult than remembering the features separately, but that this deficit is alleviated when a single probe item recognition task is used to test memory. They explained this result by suggesting that the preservation of bindings in VWM requires focused attention, and that the onset of the multi-item test display disrupted attention to the feature bindings to a greater degree than did the onset of the single-item test probe. Unfortunately, they did not provide a direct test to support their hypothesis that binding requires attention and soon after they published their report, evidence against it started to mount. For example, Gajewski and Brockmole (2006) showed that, in the face of attentional distraction, observers remember either all of an object's features or none at all, indicating that the withdrawal of attention does not lead to a break-up of bindings. In addition, Allen, Baddeley, and Hitch (2006) and Johnson, Hollingworth, and Luck (2008) have shown that a variety of attentionally demanding dual tasks fail to differentially reduce memory for bound objects compared to individual features.

Despite the forgoing evidence, however, later work suggested that maintaining proper associations between features in VWM does depend on attention. For example, some dual-task situations seem to affect working memory for concurrently maintained bound features to a greater extent than that for individual features. Such tasks include the need to remember a string of digits, monosyllabic words, or tones disrupts object-feature binding (Elsley & Parmentier, 2009) as does engaging in a multiple object tracking task during the retention interval (Fougnie & Marois, 2009). These results suggest that binding within visual working memory involves the recruitment of general attentional resources. Additionally, feature bindings appear to be more fragile than individual feature representations in VWM. For example, binding performance is selectively affected by sequential versus simultaneous presentation of memory items, suggesting that inter-item interference and overwriting by newly processed and stored items result in fragile bindings (Allen et al., 2006; see also Alvarez & Thompson, 2009; Logie, Brockmole, & Vandenbroucke, 2009).

How can the evidence for and against an attentional component to binding in VWM be reconciled? In many ways the jury is still out, but Van Rullen (2009) argues that the question itself is not well formed. He challenges the idea that all complex object recognition requires attention to bind the object's features. Instead, he proposes that two modes of binding may exist. The first is a "hardwired binding", which operates when an observer is confronted with frequently encountered natural objects. With frequent exposure, networks develop that include detectors for common feature conjunctions, eliminating the need for selective attention to perform the binding. But a second type of "on-demand" binding, mediated by attention, is needed for arbitrary or less frequently encountered feature conjunctions. This framework can explain many results that seem inconsistent with the need for attention in binding, such as the rapid categorization of real-world objects and natural scenes (see also Hommel and Colzato, 2009).

4. Visual Working Memory and the Guidance of Attention

In order to interact with the visual environment, whether to find a misplaced book, to make lunch, or to safely maneuver an automobile, observers shift their attention from place to place. While the guidance of attention through a visual display is likely influenced by perceptual factors such as local luminance, contrast, color, and motion (see Gibson, Folk, Theeuwes, & Kingstone, 2008 for a review), cognitive factors including memory are also important. To illustrate this, the following discussion considers how VWM for object identity and spatial location affect attention guidance.

4.1. Memory for Object Identity

When engaging in a visual search task, an observer has to remember not only what they have looked at, but also what they are looking for. Many theories of visual search suppose that this is accomplished by generating a *target template*, or a representation of what one is looking for, in VWM (e.g. Rao, Zelinsky, Hayhoe, & Ballard, 2002; Wolfe, 1994; Zelinsky, 2008). Once generated, these templates are used to guide search toward items sharing commonalities with the search target. For example, using eye movements as a measure of attentional allocation, Malcolm and Henderson (2009) recently showed that the ability to generate a target template led to faster searches and quicker verification of targets, indicating that target templates can also facilitate perceptual discrimination. One possible mechanism underlying this effect is captured within Wolfe's (1994) Guided Search Model which supposes that activation maps highlight likely target regions and that search templates are able to modulate activation within particular feature channels. Hence, activation for "blue" may be boosted when observers are looking for a blue car while activation for "red" or "green" may be inhibited. In this manner, blue items win the "competition" between objects in the display that each vie for the observer's attention (see also Desimone & Duncan, 1995). The usefulness of target templates, however, is not without constraints. For example, target templates are less useful when they are coded verbally rather than visually (Malcolm & Henderson, 2009; Wolfe et al., 2004) and when they provide imprecise metric information related to the target (Vickery, King, & Jiang, 2005).

In all of the preceding examples, the contents of VWM were directly related to the observer's task. One can ask whether VWM-based guidance of attention extends beyond situations where the contents of memory are task-relevant. To answer this question, researchers have engaged observers in two simultaneous tasks. In the first, observers are asked to maintain a representation of some object (or set of objects) in VWM. In the second, observers are asked to engage in search tasks that require serial shifts of attention (see Downing, 2000, for an example of an alternative approach). For example, Soto, Heinke, Humphreys, and Blanco (2005) asked observers to remember a colored shape for the duration of a trial in which they searched for a tilted line among vertical distracters. While these two tasks are independent they shared surface similarities. Specifically, the line segments appeared within colored shapes. Search times were speeded when the target appeared in a shape that matched that held in memory, and it was slowed if the memory-matching shape contained a distractor. This pattern of results suggests that attention is preferentially allocated to objects that are similar to those maintained in VWM even when doing so yields no general benefit.

Interestingly, precise perceptual matches between objects in a perceptual array and objects maintained in VWM are not necessary for such guidance (Pratt & Hommel, 2003), and similar patterns of behavior can be observed when to-be-remembered information is verbal in nature (Soto & Humphreys, 2007). Furthermore, the storage of object information in VWM can activate related concepts that are additionally capable of driving attention. For example, visual search for a particular target object such as a lock are slowed in the presence of semantically related objects such as a key (Moores, Laiti, & Chelazzi, 2003).

Collectively, the results summarized above suggest that stimulus selection is determined, at least in part, by actively maintained working memory representations, that these representations need not be task relevant, and indeed, they need not even be visual. Perhaps some of the most impressive evidence for memory-driven attentional guidance, however, comes from work with patients demonstrating visual extinction. Such patients show a reduced awareness of stimuli in the hemifield contralateral to brain lesion (usually right parietal lobe). However, Soto, Humphreys, and Heinke (2006) showed that extinction is reduced if the stimulus in the neglected hemifield matches an object that previously had to be committed to memory. This benefit was not observed if objects were previously viewed, but not remembered. This result suggests that re-entrant processes from working memory modulate attentional control and awareness.

The fact that the contents of VWM continue to bias attention allocation even when they are irrelevant to the task at hand implies that, to some degree, these effects are automatic (see also Olivers, Meijer, & Theeuwes, 2006). However, some evidence does suggest that memory-dependent biases are not mandatory. For example, Downing and Dodds (2004) asked observers to retain a shape in VWM while engaging in a visual search task. As the experiment progressed, to-be-remembered shapes would appear in the search arrays as distracters. Hence, allocating attention to the previously remembered shapes would be detrimental to performance and, indeed, observers were successfully able to ignore it. This result suggests that the contents of VWM can be used flexibly across various task demands in order to guide the allocation of attention (see also Schmidt, et al., 2002; Woodman & Luck, 2007).

The preceding discussion focused on situations where a single object was represented in VWM. However, as we view the world around us, several objects may be stored in memory. How are the more complex memories used to guide processes such as visual search? One way this has been addressed is to assess the degree to which VWM can help guide search when the precise identity of the target is unknown. Brockmole and Henderson (2005a) asked observers to search for a suddenly appearing, but unidentified, object in a real-world scene. When these objects appeared during a fixation, low-level motion signals capture gaze very quickly (usually the very next fixation) and reliably (60–80% of the time) making the task trivial. When new objects were added to a display during a saccade so that their appearance was masked by saccadic suppression (see Section 2.1), scene changes continued to attract gaze more often than expected by chance. We have argued that this continued prioritization of changes in a scene in the absence of a transient motion signal depends on VWM. For example, we have shown that reducing the viewing time afforded to observers prior to the appearance of the new object results in the effective elimination of prioritization. This result is expected if the prioritization of non-transient new objects is guided by scene memory built up over the course of viewing that includes object identities and details (see also Brockmole & Henderson 2005b, 2008; Castelhano & Henderson, 2005; Henderson & Hollingworth, 2003; Hollingworth & Henderson, 2000, 2002; Hollingworth, et al., 2001; Matsukura, et al., 2011; Tatler, Gilchrist, & Rusted, 2003).

Before concluding this section, we consider the possibility that in addition to actively maintained object representations, one's capability of storing information in VWM may affect attention allocation. Recently, Janelle Seegmiller and her colleagues (Seegmiller, Watson, & Strayer, 2011) showed that an individual's working memory capacity is correlated with his or her susceptibility to an attentional failure known as *inattentional blindness*. Inattentional blindness refers to a situation where otherwise readily perceivable information escapes awareness due to one's better or worse ability to control attention (Mack & Rock, 1998; Rock, Linnett, Grant, & Mack, 1992). The famous example that has hit the popular press is Daniel Simons and Christopher Chabris' "invisible gorilla" experiment (Simons & Chabris, 1999). In this experiment, up to 50% of observers fail to notice a gorilla walk amid a group of people playing basketball (chest pounding included!) when the participant is trying to count the number of passes one of the teams completes. This failure seemingly arises because attention is fully allocated to the ball players, leaving none to process the gorilla. Seegmiller and colleagues, however, have shown that the rates by which individuals miss the gorilla are directly related to their working memory capacity. Before watching the gorilla film, the researchers measured subjects' working memory capacity. Individuals with high working memory capacities noticed the gorilla 67% of the time while low working memory capacity individuals noticed the gorilla only 36% of the time. Hence, one's ability to store information in working memory has direct consequences on attentional control.

4.2. Memory for Object Location

Visual working memory obviously retains information that extends beyond object identities. For example, it must also encode locations of objects. For example, visual search is more efficient if an observer can remember the locations they previously searched because they can avoid revisiting them again in the future. Much less consideration has been devoted to the role spatial memory (as opposed to object memory) plays in the allocation of attention, but a few paradigms and findings have been influential in this area.

One method that has been used to explore the role that memory for object location plays in selecting items to interrogate has been to engage observers in a search task in which items are revealed a few at a time. For example, in the *preview* or *gap paradigm* (e.g., Watson & Humphreys, 1997), a search array is revealed in two stages. First, a set of distractor objects is presented—the observer is aware that none of these objects are targets. After a delay of about 1 s, another set of items, one of which is the target, is added to the display. When objects are presented in this manner, the target is found faster than in situations in which all search items are presented simultaneously. Although the exact mechanism underlying the preview effect is controversial (e.g., Donk, 2006; Olivers, Humphreys, & Braithwaite, 2006), it is apparent that some memory for the locations of the old and new items must be involved because once the second array appears, it is impossible to perceptually distinguish the two groups of items.

Another approach to demonstrating memory for spatial locations was taken by McCarley, Wang, Kramer, Irwin, and Peterson (2003). Once again, observers were engaged in a visual search in which only a subset of the search array was visible at a given moment. Using an eyetracker, they monitored eye movements in real-time and used them to trigger updates to the visible array. During each fixation, three letters were visible: one at the locus of fixation and two in peripheral positions. If the fixated letter was not the target, the observer had to shift his or her gaze to one of the other two visible letters. Critically, one of these was a new letter while the other letter was a decoy having been fixated previously. Their results showed that observers tended to avoid the old letters. Furthermore, by varying the lag (i.e., number of intervening items and saccades) between the first presentation of a letter and its use as a decoy, they determined that at least the last four positions were retained in VWM.

In addition to showing that attention is biased away from previously attended locations, a variety of other findings suggest that spatial locations maintained in VWM are used to guide attention. For example, visual search is slowed when observers are asked to remember a series of spatial locations during a visual search task (Oh & Kim, 2004; Woodman & Luck, 2004), presumably because the additional task interferes with the observers' ability to remember the locations of the searched and the to-be-searched items in the display. The manner in which object locations are retained in memory may also offer resolution to a long-standing debate within the attention capture literature. *Attention capture* refers to the notion that certain visual properties or events in a display can reflexively and automatically draw attention. One contentious issue within this discussion in particular is whether or not newly appearing objects in a display are capable of capturing attention in this manner. There is as much evidence in favor of this claim (e.g., Chua, 2009; 2011; Davoli, Suszko, & Abrams, 2007; Enns, Austen, Di Lollo, Rauschenberger, & Yantis, 2001; Rauschenberger, 2003; Yantis & Hillstrom, 1994; Yantis & Jonides, 1996) as there is against it (e.g., Brockmole & Henderson, 2005a; Boot, Brockmole, & Simons, 2005; Chua, 2009; 2011; Franconeri, Hollingworth, & Simons, 2005; Hollingworth, Simons, & Franconeri, 2010). Recently, Chua (2009, 2011) has argued that evidence for and against new object capture can be explained by successes and failures of VWM, respectively. In order to realize a new object has appeared in a display, some memory for the locations of pre-existing (i.e., "old") objects is necessary. By systematically manipulating the extent to which the locations of old objects are attended, and thus encoded into VWM, Chua has been able to eliminate capture from paradigms that otherwise show it, and reveal capture in paradigms that otherwise do not show it. Thus, at least in this recent iteration of the new object paradigm, VWM for old object locations appears to be the key to new object capture. Collectively, then, the various studies highlighted in both this and the previous section demonstrate that remembering an object's identity and location can be profitably used to guide attention as we interrogate our visual surroundings.

5. Attention and Visual Long-Term Memory

In contrast to short-term memory, visual long-term memory has no clear limit on its capacity or storage duration. In one striking demonstration of this, after being shown hundreds of photographs for just a few seconds each, observers are able to recognize the pictures they saw even after a retention period of an entire year (Nickerson, 1968; see also Standing, 1973; Standing et al., 1970). Access to this LTM store relies on attention in much the same way as VWM, as it is the objects that are attended during the perception of the environment and that are rehearsed in VWM that may be retained long-term. However, the long-term maintenance of information in memory is accomplished without the need for sustained attention. As the above example shows, even with long delays between study and test, where attention has been removed from an object, its representation in VLTM perseveres.

In addition to enabling the accumulation of information in memory beyond the limits of VWM, long-term memory can also modify the allocation of attention to a visual display. For example, the spatial relationships among objects in an environment are relatively constant. To illustrate, we suspect that the arrangement of furniture in your living room remains relatively unchanged from day to day. Even objects that are moved regularly, such as utensils and small electric appliances in your kitchen are generally located in a few predictable locations. This redundancy in visual experience allows observers to eliminate the need to constantly execute a detailed serial search for a desired object. In the literature, this effect is called *contextual cuing* and was first studied by Chun and Jiang in 1998. They asked observers to search for a "T" target among an array of "L" distracters. They created two kinds of trials. Across the experiment, a subset of the search arrays were consistently repeated so that the arrangement of distracters perfectly predicted target position. Observers were sensitive to this repetition and, as a result, the efficiency of visual search, as measured by response times, increased across repetitions. Later experiments would show that these decreases in RT were directly attributable to more direct guidance of attention to the targets as fewer (Brockmole & Henderson, 2006a; Peterson & Kramer, 2001a,b) and more direct eye movements (Brockmole & Henderson, 2006a; Brockmole & Vo, 2010) to the target are observed after learning (but see Kunar, Flusberg, Horowitz, & Wolfe, 2007).

Since its inception, contextual cuing has been identified in a wide range of stimuli and viewing conditions. By doing so, researchers have attempted to determine the components of visual experience that are encoded into VLTM, the aspects of memory that are functional in guiding attention, and the boundary conditions that define the scope and scale of learning. Although contextual cueing is observed across many visual contexts, the learning principles involved vary according to circumstances. For example, both quantitative and qualitative differences have been observed depending on whether the repeated contexts are defined by simple stimulus arrays or by real-world scenes. Indeed, repeated contexts defined by color photographs are learned faster and give rise to greater benefits than contexts made up of letters (Brockmole & Henderson, 2006a). Scene-based contextual cuing also seems to rely heavily on global pattern analysis (Brockmole, Castelhano, & Henderson, 2006; Ehinger & Brockmole, 2008), categorical identity information (Brockmole & Henderson, 2006a; Brockmole & Vo, 2010), and conscious awareness of the predictive regularities (Brockmole & Henderson, 2006a;) while local elements (Brady & Chun, 2007; Jiang & Wanger, 2004; Kunar, Flusberg, Horowitz, & Wolfe, 2007), surface features (Jiang & Song, 2005), and implicit learning mechanisms (Chun & Jiang, 1998; but see Smyth & Shanks, 2008) play a more prominent role in the development of memory for consistently arranged arrays of letters or abstract shapes. Because the contextual cuing paradigm reveals different types of learning behavior depending on the testing environment, one must question why such differences arise.

Recently, we have argued that the quality and extent of contextual learning is correlated with the absence or the presence of semantic information (Brockmole, Hambrick, Windisch, & Henderson, 2008; Brockmole & Henderson, 2006a, Brockmole & Vo, 2010). The use of semantic information to guide search to learned targets, when available, would have several consequences that fit well with the contrasts drawn above between scenes (semantically rich) and letter arrays (semantically impoverished). First, it would reduce the reliance on visual features and local statistical relationships. Instead, emphasis would be placed on the analysis of global patterns (Brockmole et al, 2006) and of categorical identity information (Brockmole & Vo, 2010; Goujon, 2011). Second, by enabling a dual-coding of visual properties and semantic labels, semantic information could facilitate the discrimination of different scenes and improve the recognition of familiar displays (Brockmole & Henderson, 2006a). Third, semantically rich displays could lead to conscious awareness of contextual regularities, which in turn could enhance their consolidation and retrieval in memory (Brockmole & Vo, 2010; however, Goujon, 2011; Goujon, Didierjean, & Marmèche, 2007, 2009).

Direct evidence for a semantic influence in contextual cuing within scenes comes from a variety of observations. For example, when repeated scenes are inverted, which makes them more difficult to identify, the development of contextual cuing is slowed and its overall benefit reduced relative to upright scenes (Brockmole & Henderson, 2006a). In addition, contrary to simple displays (Brady & Chun, 2007), contextual cuing in scenes survives changes to local arrangements of objects, provided that the identity of the scene is not altered (Brockmole et al., 2006). Finally, contextual cuing is possible when scene categories predict target position, even if scene exemplars are never repeated. For example, contextual cuing effects have been demonstrated when targets were always located on pillows in (nonrepeated) bedroom scenes (Brockmole & Vo, 2010), or when multiple scene categories each predicted the (x,y) location of a target in space independent of object arrangement (Goujon, 2011). Nonetheless, the semantic hypothesis does not, at present, clearly predict conscious awareness of contextual regularities. While Brockmole and Vo (2010) obtained evidence for explicit cuing in their study, Goujon observed implicit learning in hers, whether semantically rich displays were defined by real-world scenes (Goujon, 2011) or visually sparse displays composed of numbers (Goujon, et al., 2007) or words (Goujon, et al., 2009). Whether and to what extent the presence of semantic information is really required for conscious awareness therefore remains an open question (see Goujon & Brockmole, 2012).

Other aspects of long-term memory for object or scene identity are also used to guide attention during visual search. For example, target detection is facilitated if a target object is consistently presented with the same distractor objects, compared to situations where the distractor and target objects are uncorrelated (citation). Additionally, the visual knowledge stored in LTM regarding semantic associations between objects influences search. When searching for a target object (e.g., nails) that is—unknown to the observer—absent from a display (hence the target cannot attract attention itself), the presence of a semantically consistent object (e.g., hammer) draws attention because, in our experience, these objects tend to be co-located (citation). Thus, the visual information accumulated over one's lifetime can be brought to bear on search tasks in an effort to increase efficiency.

Recent studies have further revealed that embodiment is an important mediating factor in the relationship between attention and VLTM. One way in which such mediation occurs is through physical expertise. Experts attend to items related to their area of expertise differently than non-experts (e.g., Calvo-Merino, Ehrenberg, Leung, & Haggard, 2010; Gauthier, Curran, Curby, & Collins, 2003). This type of "expert" attention is often beneficial for later memory of such items (e.g., Dijkstra, MacMahon, & Misirlisoy, 2008), although it can be detrimental. For example, expertise can give rise to false recognition, as demonstrated by Yang, Gallo, and Beilock (2009). In their study, expert and novice typists provided likeability ratings for a list of 16 visually presented letter dyads (e.g., *FV*, *HC*). Following the rating phase, participants were given a surprise recognition test in which they had to indicate which items from a list of 32 letter dyads they had seen in the previous phase. Remarkably, expert typists were more likely to falsely recognize dyads that would be easier or more fluent to type. The mechanistic account offered for this effect was one of motor simulation: expert typists, when presented with letter dyads, are thought to automatically simulate the corresponding motor program for typing those dyads. This is in line with findings of greater neural activation in premotor areas when people view familiar compared to unfamiliar actions (e.g., Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005). Yang et al. proposed that simulating dyads of high motor fluency during test could give rise to feelings of familiarity, thus causing new dyads to be misremembered as having been previously presented.

The connection between attention and VLTM may also be mediated by the body more directly. Recalling our discussion in Section 2.1, it was noted that objects in the hands benefit from prioritized (Reed et al., 2006, 2010) and prolonged (Abrams et al., 2008) attention, which in turn yields improved VWM for such objects (Tseng & Bridgeman, 2011). Thus, a reasonable supposition would be that hand proximity should also facilitate higher-order cognitive processes like visual learning and VLTM. Davoli, Brockmole, and Goujon (2012) addressed this hypothesis by having participants perform a contextual cueing task either with their hands alongside the display or in their laps. When displays remained identical across repetitions, cueing effects did not differ between postural conditions, thus suggesting that there was not a universal benefit for learning or VLTM near the hands as might have been predicted. However, when displays remained structurally identical but changed color scheme across repetitions, learning was actually impaired near the hands! Davoli et al. explained this pattern by arguing for a bias toward processing item-specific detail near the hands, which fosters discrimination between objects that are otherwise identical. Such a bias would be beneficial for making action-based decisions about objects (e.g., eating the ripe apple but discarding the rotten), but could impair one's ability to abstract visual commonalities across similar objects. Thus, when it comes to deciding whether to hold or not to hold to-be-learned material, the answer is likely dependent upon what the goal of learning is.

6. Concluding Remarks

In this chapter, we considered a variety of interactions between visual attention, visual working memory, and visual long-term memory. We have seen that attention, in many ways, acts as a gatekeeper to VWM. We have also reviewed evidence that attention plays an important role in the maintenance of information in VWM as it affects the capacity of VWM as well as the quality of the representations maintained therein. Finally, we have described many examples of tasks and situations in which the contents of both VWM and VLTM reciprocally affect the guidance of attention through visual displays. In an effort to reinforce the interactions we have described in this chapter, we close by putting them in to single context: Notre Dame Football.

If we utilize the events that unfold during an American football game, we can consider a variety of interactions between attention and memory, as well as the consequences of these interactions (see Figure 3). Because

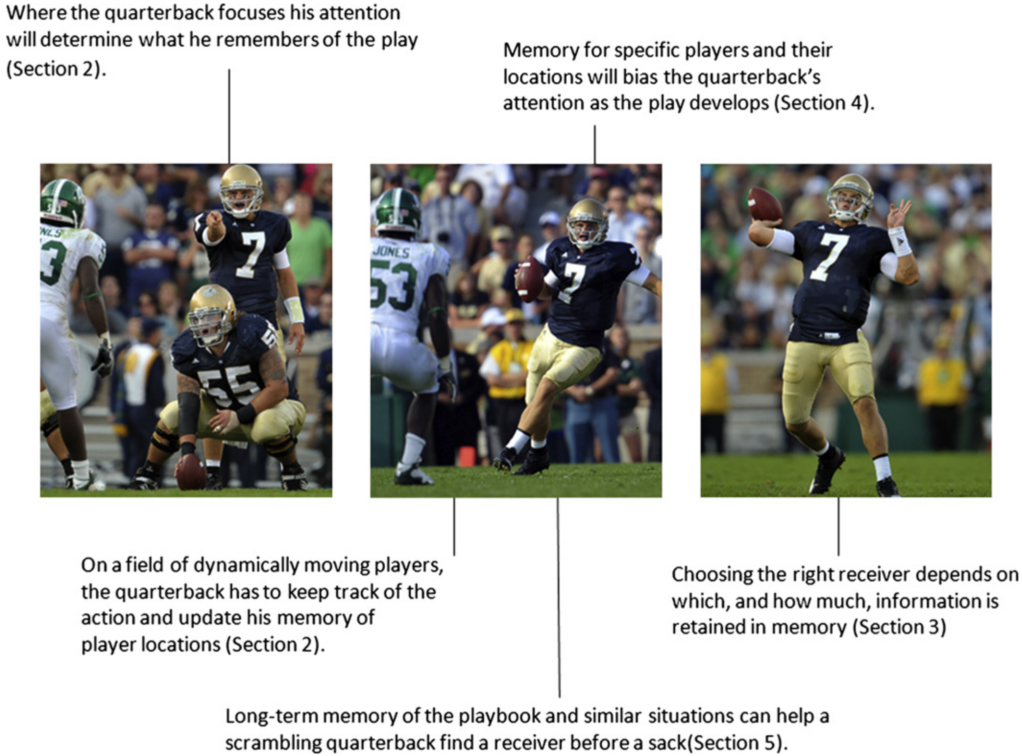

Figure 3 Football provides just one real-world context in which the interactions between attention and memory are readily apparent. (Photo credits: Matthew Cashore; used with permission.) (For color version of this figure, the reader is referred to the web version of this book.)

football plays involve 22 players, each moving dynamically over a period of several seconds, they constitute events during which attention will be allocated to multiple objects and locations and for which working memory representations must be constructed to maintain awareness of the action without constant perceptual access to the entire field of play. Furthermore, because football plays are repeatedly studied and rehearsed at practices, there is ample long-term memory that can be used to support in-the-moment behavior.

Let's first consider the consequences of attentional control on the formation of working memory that we have been discussing, from the perspective of a hypothetical quarterback (the player who controls the offense) preparing to initiate a play (left panel of Figure 3). His memory representations provide, among other things, indices of player identities and locations. In this manner, a quarterback looking to his left can still maintain a reasonable understanding of the players to his right. While doing this, we know from Section 2, that both the dynamics of the quarterback's attentional control and VWM are inherently limited. As a result, a quarterback surveying the defense will not equally allocate his attention to each defender nor accurately represent all players in memory. Rather than obtaining a random sample of information, the quarterback can allocate attention strategically, perhaps to certain players who might, by their positioning, reveal the defense's strategy. By making such choices, the quarterback can fill VWM with what he believes to be the most important details. As the play then begins (middle panel of Figure 3), players on both the offense and defense will move and as a result, some will become more or less important to the play. As this happens, our quarterback's representations of player positions can be fluidly updated. However, such updates are not without cost. For example, running to his right, the quarterback may have more difficulty remembering the positions of the defenders to his left who continue to pursue him.

In Section 3, we saw that in addition to gating access to VWM, attention determines the contents and "refresh rate" of the VWM store. For example, the number of items (e.g., defenders, receiving routes, and the first-down marker) that our hypothetical quarterback can remember is directly related to his ability to vigilantly attend to task-relevant information. The better he can ignore task-irrelevant information—the crowd, the players on the sidelines, the referees—the better he will be able to remember the actions of the offense and defense. Furthermore, by allocating attention to specific components of his VWM representation of the play, the quarterback can protect the most critical aspects of his memory (the previous location of his primary receiver during a scramble, for example).

After the contents of VWM are initially determined by the dynamics of attentional control, the resulting memory representations can be used in turn to bias the allocation of attention to space (a vicious cycle is brewing!). In Section 4, we looked at ways in which memory for object identity and object location can enter into attentional control decisions. On the football field, the quarterback's decision regarding whom to throw to will depend on this interaction (right panel of Figure 3). After scanning the right side of the field, the quarterback may turn to this left, keeping in mind the action to his right. Representations regarding the previous positions of particular players can inform the quarterback's decision to either throw to his left or to shift his attention back to the right to throw to a better option. Similarly, as we discussed in Section 5, the contents of VLTM are useful during a play. Should a quarterback find himself scrambling to avoid defenders, for example, long-term memory for the playbook, practice, and similar situations can give him the wherewithal to find an outlet receiver, an action that requires quick and accurate shifts of attention to find his open man.

Our football example is, for sure, simplified and over-generalized (otherwise there'd be no need for the first 12,000 words of this chapter), but we think it nevertheless puts the research endeavors described in this chapter into helpful context. In fact, it is a useful context for considering lab-related research questions as well. One simple football play can force us to ask to what extend attention can be studied out of context with memory or, vice versa, to what extent memory can be studied without considerations of attention. In our view, the various relationships we have described and addressed in this chapter, at a minimum, suggest that attention and memory mechanisms cannot be studied in isolation, and that it is more fruitful to consider the implications each has on the other. Like Frank Sinatra sang of love and marriage (Cahn & Van Heusen, 1955), when it comes to attention and memory, you can't have one without the other.

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