

The role of working memory and long-term memory in visual search

Geoffrey F. Woodman

Vanderbilt University, Nashville, TN, USA

Marvin M. Chun

Yale University, New Haven, CT, USA

Models of attentional deployment in visual search commonly specify that the short-term, or working memory, system plays a central role in biasing attention mechanisms to select task relevant information. In contrast, the role of long-term memory in guiding search is rarely articulated. Our review of recent studies calls for the need to revisit how existing models explain the role of working memory and long-term memory in search. First, the role of working memory in guiding attentional selection and search is much more complex than many current theories propose. Second, both explicit and implicit long-term memory representations have such clear influences on visual search performance that they deserve more prominent treatment in theoretical models. These new findings in the literature should stir the conception of new models of visual search.

Visual search tasks have long been used by cognitive scientists to study the deployment of attention to targets within complex arrays of distractor stimuli (Green & Anderson, 1956; Green, McGill, & Jenkins, 1953; Neisser, 1964). An attractive feature of the visual search task is that it taxes perceptual processing while presumably placing minimal demands on memory in contrast to other paradigms popularized during the same period (e.g., Sternberg, 1966). Technically speaking, a subject only needs to remember what to search for and how to respond to its presence or absence. Such considerations may have helped make visual search such a popular tool for

Please address all correspondence to Geoffrey F. Woodman, Department of Psychology, Wilson Hall, 111 21st Avenue South, Vanderbilt University, Nashville, TN 37240-1103, USA. E-mail: geoffrey.f.woodman@vanderbilt.edu

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studying perceptual processing of features and objects (e.g., Treisman, 1988; Wolfe, 1994, 1998; Yantis & Jonides, 1984). Ironically, however, the field has begun to shift its focus from perceptual processing to an increased appreciation for the role of memory in visual search. For example, one may ask whether a memory representation of the target is formed after it is detected. In addition, do observers encode distractors that were attended during a visual search trial? More specifically, researchers have recently vigorously debated whether distractor locations are tagged by memory representations or not during visual search (e.g., Horowitz & Wolfe, 1998, 2003; Kristjánsson, 2000; von Mühlénen, Müller, & Müller, 2003). If memory for targets and or distractors exists, what types of memory stores are involved (e.g., Shore & Klein, 2000)? Although these issues are far from being resolved, recent research has shed light upon how memory representations of targets and nontarget objects guide attention during visual search. This paper will survey the most current research on how different memory systems impact visual search. Several unifying themes emerge from this review.

Memory representations exert their effects on visual search both within trials and across trials, and so we organize our discussion accordingly. Within a single trial of visual search, short-term, or working memory, representations of targets and distractors contribute to efficient processing. Across trials, long-term memory representations of targets and distractors also influence search. This scheme of organizing memory effects on search is the same as that introduced in Shore and Klein's excellent review of this issue (2000).¹ Our discussion will focus on the many new studies that have emerged since their review to further clarify how different memory systems represent targets and distractors to guide search. We note an increasing need to update models of visual search in light of recent new findings in the literature. For example, models of visual search often propose that target representations, or templates, are maintained in visual working memory and guide attention to select similar items from the currently available visual

¹ Because visual search tasks are typically comprised of discrete trials, it is useful to distinguish different roles of memory according to how memory influences performance within or across trials. We assume that within-trial effects are best subserved by working memory that has limited-capacity and requires active maintenance to perform a task at hand. Because target and distractor locations typically change unpredictably from trial to trial, the system should reset itself on each new trial to minimize debilitating proactive interference. Such resetting is naturally performed by the working memory system, according to theories of memory and models of visual search. Across-trial influences appear to be best explained by LTM processes that have larger capacity and less susceptibility to interference and erasure, serving to extract useful regularities that may occur over time. Although we will discuss this distinction in more detail later, we acknowledge that the distinction between working memory and LTM is a simplification, and in fact, we will conclude that visual search benefits from both working memory and long-term memory systems.

information (Bundesen, 1990; Desimone & Duncan, 1995; Duncan & Humphreys, 1989). However, the relationship between working memory and search is more complicated than suggested by these models. In contrast, models of attentional deployment during search offer scant treatment of how long-term memory representations of targets and distractors influence the efficiency of visual search, but a growing body of studies point to a prominent role for long-term memory.

VISUAL WORKING MEMORY AND SEARCH

Virtually every general model of cognitive processing posits that temporary memory (i.e., working memory) storage is essential for complex information processing (e.g., Anderson, 1993; Meyer & Kieras, 1997). Working memory is believed to support our ability to retain, accrue, and manipulate information over short periods of time. For example, it has been proposed that our working memory capabilities support sentence construction during language use (e.g., Just & Carpenter, 1980), the integration of information across blinks and saccades (e.g., Irwin, 1992; Irwin & Andrews, 1996), and complex problem solving by representing possible solutions (e.g., Newell & Simon, 1972). We have focused the current discussion on theoretical proposals and empirical studies of the involvement of working memory in visual search. Because the capacity of the visual working memory store appears to be limited to a small number of items (e.g., Irwin & Andrews, 1996; Lee & Chun, 2001; Luck & Vogel, 1997; Simons, 1996; Vogel, Woodman, & Luck, 2001) it requires careful utilization when the visual system is overloaded with information, as it is during demanding visual search tasks.

In visual search, researchers have proposed two ways that working memory may be vital. One proposed use is that each attended item may be transferred into working memory while search is performed (Bundesen, 1990; Duncan & Humphreys, 1989; Treisman, 1988). According to such an account, a stimulus that draws attention to its self (e.g., a waving sports fanatic) will automatically enter the visual working memory of an observer (e.g., a basketball player preparing to shoot a free throw). The majority of these models propose that attended items need to be entered into visual working memory to compare with a target representation that is maintained in visual working memory (Bundesen, 1990; Duncan & Humphreys, 1989). The second related proposal is that representations stored in visual working memory during search serve to bias the deployment of attention to similar items. In this way, the maintenance of an object representation in visual working memory largely determines what inputs are selected during search (Bundesen, 1990; Desimone & Duncan, 1995; Duncan & Humphreys, 1989).

We first provide a brief review of several of the most influential models of selective processing during visual search.

One of the first theories proposed to explain the differences that exist between efficient and inefficient visual search tasks was the Feature Integration Theory (FIT) of Treisman and colleagues (Treisman, 1988; Treisman & Gelade, 1980; Treisman & Sato, 1990; Treisman, Sykes, & Gelade, 1977). FIT proposes that certain visual search tasks are inefficient because the individual objects in the arrays require focused perceptual attention in order for their features to be bound into object representations. Specifically, FIT proposes that the deployment of focused attention to an object location serves to bind the features of that object together. After an object's features are bound, that representation is stored as an *object file*. One possible interpretation of an object file is that it is a representation in visual working memory. Thus, one interpretation of FIT leads to the prediction that focusing attention on an object leads to its encoding into visual working memory.

Duncan and Humphreys (1989) proposed an alternative account of processing during visual search. They hypothesize that there is a limited amount of attention that can be distributed across multiple items in the visual field. The more attention allocated to a given object, the greater the chance that a perceptual representation of this item will enter working memory, thereby allowing a behavioural response about that object to be made. What determines how much resource is allocated to each item? Duncan and Humphreys propose that resource allocation depends upon the match between each perceptual representation and a target template maintained in visual working memory. This and other models of visual search do not fully specify what constitutes a target template, however, it can be assumed to be either a picture-like representation or an abstract representation that defines features. For example, when the task requires searching for a red square, it is proposed that observers store a red square (or an abstract description of a red square) in working memory, and the priority of each perceptual representation for transfer into visual working memory is therefore greatest for red items, square items, and especially red-square items. In this manner, the current contents of visual working memory are posited to bias the transfer of similar perceptual representations into working memory. Specifically, Duncan and Humphreys go on to propose that if during search visual working memory "... is filled it must be flushed before the entry of new information can begin" (p. 446). Thus, Duncan and Humphreys' model of attention makes very explicit claims about how visual working memory is utilized during visual search.

Duncan and Humphreys (1989) are not the only theorists to propose that visual working memory is essential for efficiently processing complex arrays of objects. For example, Bundesen (1990) proposed a powerful

computational model of visual attention that shares several conceptual characteristics with the model of Duncan and Humphreys. Bundesen's Theory of Visual Attention (TVA) is a flexible computational model in which representations are entered into visual working memory, and at the same time categorized, based on their similarity to a target representation also maintained in visual working memory. Yet another influential model of attentional selection is the biased competition account of Desimone and Duncan (1995). The biased competition account proposes that representations compete for access to limited-capacity mechanisms of the brain. Examples of scarce resources for which representations might compete are the receptive field of cells, representational space in working memory, and access to response execution mechanisms. This account has been applied to visual search tasks in considerable detail. The biased competition account proposes that the visual system becomes biased to process target-like objects by maintaining a representation of the expected target in visual working memory. This will tend to strengthen matching representations, allowing them to compete more effectively for limited resources. The strongest evidence for the maintenance of target templates during search comes from single-unit recording studies.

Chelazzi, Miller, Duncan, and Desimone (1993) recorded from neurons in the temporal lobe of macaque monkeys while they performed a delayed match-to-sample (DMS) task. In this task, a sample item was presented, and after a delay interval an array of several items was shown. The subject then made a motor response indicating whether the sample item (the target) was present or where it was located. Chelazzi et al. found that the neurons that coded for the target maintained an elevated firing rate during the delay intervals. This elevated firing rate was interpreted as evidence that a working memory representation of the target was being maintained during the retention interval. In addition, it was hypothesized that this memory representation provides a bias signal to the neurons that perform perceptual analysis. This bias signal in turn increases the baseline firing rate and therefore induces a competitive advantage for neurons that selectively respond to the target.

The importance of visual working memory representations during visual search in the biased competition account is emphasized by this quote: "Visual search simply appears to be a variant of a working memory task, in which the distractors are distributed in space rather than time" (Desimone & Duncan, 1995, p. 207). Although the findings of the single-unit studies provide valuable insight regarding how DMS tasks are performed, it is quite possible that visual search is performed differently when the task does not explicitly require visual working memory storage of the target. For example, in typical visual search tasks with human observers, the target remains constant for many minutes or even throughout the entire experiment. It is

possible that when the identity of the searched-for target is stable across many trials that task performance becomes automated and can be driven by long-term memory representations (e.g., Logan, 1988). Thus, it will be important to confirm that human and nonhuman primate subjects rely upon the same mechanisms when performing identical cognitive tasks.

In summary, we have discussed the theoretical underpinnings of two types of interactions between perception and working memory. First, several theories of attention propose that attended items are obligatorily transferred into visual working memory during each trial of visual search (Bundesen, 1990; Duncan & Humphreys, 1989; Treisman, 1988). The second type of posited interaction between perception and working memory is that working memory representations are maintained throughout each trial of visual search to influence perceptual mechanisms in a top down manner, such that items similar to those represented in visual working memory are automatically selected for preferential processing (Desimone & Duncan, 1995; Duncan & Humphreys, 1989). These models make specific predictions that can be empirically tested, as we shall review below.

Are all attended objects represented in visual working memory during a visual search trial?

It is very difficult to determine what is being stored in visual working memory during the performance of a task such as visual search. However, several recent studies have sought to determine whether representations of items in a search array are stored in visual working memory, or in any type of memory store, during a visual search trial. In particular, a recent debate in the literature surrounds the proposal that visual search requires no visual working memory resources at all. Specifically, Horowitz and Wolfe (1998) have proposed that no information about the identity or location of objects is accrued in visual working memory during search. In two different conditions, subjects searched for rotated “T”s embedded in arrays of rotated “L”s. In one condition, the search arrays were static (as in most visual search experiments). In the other condition, the locations of the objects changed every 100 ms during the 2.3 s trial. They reasoned that if information about the location of the target accrues slowly over time in memory, then subjects should be less efficient at finding the target when the object locations change every 100 ms because the accrual process would have to restart with every change. Horowitz and Wolfe found that the slopes of the search functions did not differ between the static and the changing displays, indicating that subjects were just as efficient at finding targets in the changing as in the static condition. From these results, Horowitz and Wolfe argued that visual search

does not rely on information that accrues in visual working memory or any other memory store.

The claim for amnesic search has triggered an intense debate in which several researchers have argued that the conclusion may apply only to the task and set of conditions employed by Horowitz and Wolfe (Gibson, Li, Skow, Brown, & Cooke, 2000; Horowitz & Wolfe, 2001, 2003; Kristjánsson, 2000; Shore & Klein, 2000). For example, Shore and Klein (2000) suggest that the results obtained by Horowitz and Wolfe were due to subjects trading off accuracy for speed in the dynamic condition in which the locations of the items changed during each trial. Other researchers have proposed that performance in the dynamic condition becomes less efficient when larger search arrays are used (Kristjánsson, 2000), or performance in the dynamic condition could be due to observers adopting a strategy of statically attending to one quadrant and waiting for the target to appear there (von Mühlénen et al., 2003).

Beyond the Horowitz and Wolfe paradigm, the necessity of working memory in search can be tested with a dual-task interference approach. Woodman, Vogel, and Luck (2001) tested whether visual working memory was needed during a search task that required serial shifts of attention (Woodman & Luck, 1999, 2003). The logic of the approach was as follows. If attended representations are encoded into visual working memory during search, then filling the visual store to capacity with irrelevant information should decrease search efficiency and possibly even prohibit the performance of visual search. Thus, they required observers to remember up to four colours or shapes while performing a demanding visual search task and compared visual search efficiency to a condition in which subjects performed the same visual search task in isolation. They found that the efficiency of search, as measured by the slope of the $RT \times$ Set size functions, did not differ between the dual-task and single-task conditions (Figure 1B). Several models (e.g., Bundesen, 1990; Duncan & Humphreys, 1989) predict the opposite result because nontarget items not held in visual working memory are likely to be reselected by attention and therefore decrease the efficiency with which the target object can be processed.

A related prediction is that if working memory is necessary for search, then subjects should be less accurate at the working memory task when more items in the search array need to be processed. In contrast, Woodman et al. (2001) found that regardless of the set size of the search array the same amount of information could be maintained in visual working memory. That is, performing search displaced approximately the same amount of information from visual working memory across the set sizes tested (for example see Figure 1C). This result runs counter to predictions made by models that propose the contents of visual working memory are expelled if the visual store is full when search is performed (e.g., Duncan & Humphreys,

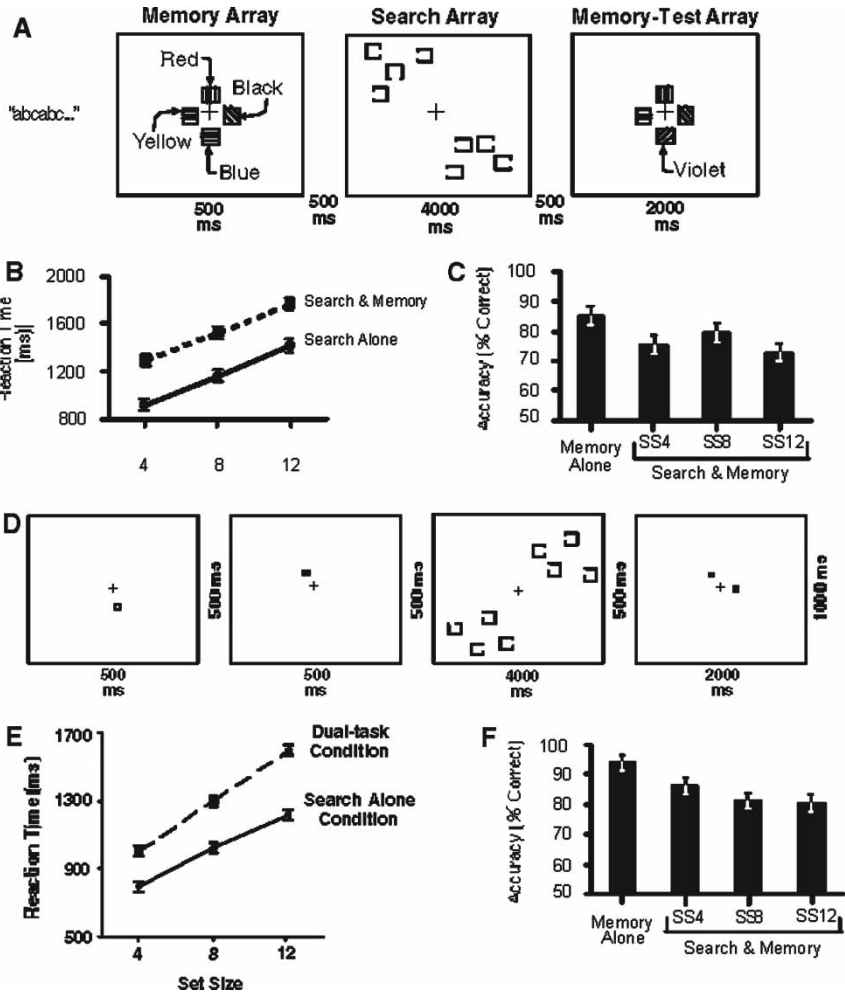


Figure 1. Example stimuli and findings from Woodman and Luck (2004) and Woodman et al. (2001). Sequence of stimuli presented in Experiment 2 of Woodman et al. (2001) (A). Visual search reaction time with and without an object working memory load (B). Performance on the visual working memory task with and without search during the retention interval (C). Example of the stimulus sequence used in Woodman and Luck (in press) (D). Visual search RT data in the search alone and search-plus-spatial-memory task (E). Spatial change-detection accuracy when the two locations were maintained in isolation compared to during visual search at different set sizes.

1989). In summary, this study found little evidence that supports the idea that representations of searched-for objects need to be maintained in visual working memory during each trial.

An interesting and important aspect of visuospatial working memory is that it not only represents objects, but it also can also maintain spatial

location information. Moreover, the working memory stores for objects and for spatial locations may be separate from each other or rely upon different aspects of the visuospatial subsystem (e.g., Baddeley & Logie, 1999; Goldman-Rakic, 1996; Logie, 1995). Visual search requires attention to be shifted from one location to another (Treisman & Gelade, 1980; Wolfe, 1994), and it may also benefit from tracking of visited locations (Klein, 1988). This raises the possibility that spatial working memory may be necessary for visual search.

Accordingly, two research groups independently tested the hypothesis that concurrently maintaining representations of spatial locations during each search trial interferes with the efficiency of a demanding visual search task. Both Oh and Kim (2004) and Woodman and Luck (2004) used dual-task methodology similar to that of Woodman et al. (2001) but, instead of requiring subjects to remember objects during visual search, observers needed to remember several spatial locations. The studies found that maintaining even a relatively small number of locations interfered with the efficiency of search compared to when the same search task was performed in isolation, see Figure 1E. These findings are consistent with existing research demonstrating that spatial working memory tasks tax spatial attention mechanisms presumably because spatial attention is being focused on the to-be-remembered locations (e.g., Awh & Jonides, 1998; Awh, Jonides, & Reuter-Lorenz, 1998). Thus, the dual-task interference results indicate that the same spatial attention mechanism is involved in both visual search and the active maintenance of spatial locations. Moreover, the differential effects of maintaining object (Figure 1A) versus spatial location representations (Figure 1D) provides further evidence supporting theoretical proposals that separate stores or mechanisms exist for object and spatial working memory functions (e.g., Baddeley & Logie, 1999; Goldman-Rakic, 1996; Logie, 1995).²

A growing number of studies also suggest that visual search tasks that require eye movements to the search elements are supported by a memory system that retains the locations of the last four or so foveated locations. Specifically, Peterson, Kramer, Wang, Irwin, and McCarley (2001) recorded eye movements while subjects performed visual search for a small form-defined target. They found that subjects very rarely made eye movements back to an object if it had recently been foveated; however, the probability of refixation increased dramatically if four other objects were fixated since the

² The majority of evidence supports a distinction between spatial and object working memory stores, but this does not mean that object and spatial working memory representations cannot be linked (e.g., Jiang, Olson, & Chun, 2000; Rao, Rainer, & Miller, 1997). In fact, it is likely that one role of attention is to bind information across such separate working memory stores (e.g., Wheeler & Treisman, 2002).

fixation of any given object. These findings seem closely tied to the inhibition of return (IOR) phenomenon in which subjects are slower to respond to a target presented at a previously attended location than at a previously unattended location (for a thorough discussion see Shore & Klein, 2000). Interestingly, some recent findings suggest that IOR is most reliably observed during visual search when the search task involves eye movements to objects in search arrays that remain visible while items were probed for inhibition (Klein & MacInnes, 1999; Müller & von Mühlennen, 2000). Finally, Castel, Pratt, and Craik (2003) found that performing tasks that demanded the use of spatial working memory prevented subjects from showing the IOR effect. This suggests that spatial working memory may play an important role in maintaining representations that contribute to the IOR phenomenon.

We draw three general conclusions from the studies discussed above. First, empirical results do not support theories that propose that a target must be represented in visual object working memory for attention to be efficiently deployed to that object in a search array. Second, actively maintaining *spatial locations* appears to draw upon the same mechanisms that are taxed during demanding visual search tasks, unlike maintaining *objects* in working memory. Finally, visual search tasks that require subjects to make eye movements may engage memory for tagging visited items that is less reliably recruited in visual search paradigms where covert selection plays the dominant role. Further research will be needed to clarify this issue among others, such as the involvement of the central executive component of working memory during a visual search trial (de Fockert, Rees, Frith, & Lavie, 2001). For example, a recent study demonstrated that occupying central executive processes severely impaired the efficiency of visual search (Han & Kim, 2004).

Is attention automatically drawn to items that match the contents of working memory during visual search?

A central tenant of many models of visual search is that target template representations are maintained in visual working memory to bias attention to select similar items (Desimone & Duncan, 1995; Duncan & Humphreys, 1989). This proposal assumes that attention is automatically biased to select incoming information that is similar to that stored in visual working memory. Some evidence supporting this assumption has been found using delayed-match-to-sample tasks with monkeys (Chelazzi et al., 1993), and attentional blink (Pashler & Shiu, 1999) and cueing studies (Downing, 2000; Pratt & Hommel, 2003) with human subjects. However, several recent studies with monkey and human observers suggest that the contents of

working memory can be used flexibly to bias attention mechanisms and in some cases working memory resources may not be needed at all for efficient search.

In several experiments, Woodman and Luck (in press; see also Downing & Dodds, 2004; Woodman, 2002) extended the logic of previous studies (i.e., Downing, 2000; Pashler & Shiu, 1999) to the domain of visual search. Specifically, they tested the hypothesis that attention is automatically deployed to items that match those stored in visual working memory during a visual search trial. The experiments were designed so that subjects had no reason to strategically shift attention to items that are similar to those represented in visual working memory. That is, the subjects were provided with an incentive for not attending to items that match those in working memory because the matching search item was never the target in the search task (for use of similar logic see Folk, Remington, & Johnston, 1992). Moreover, an item matching the representation held in visual working memory as not present in the visual search array on every trial. If the distractors that match the contents of visual working memory do not interfere with visual search, this would indicate that items matching those in visual working memory do not capture attention in a strongly automatic manner. They consistently found that subjects were not slower to find the target when a distractor matched an object represented in visual working memory. These findings suggest that attention is not automatically deployed to items simply because they are similar to an object in memory, but instead the contents of visual working memory can be used adaptively to guide attention away from items that are known to be nontargets. A highly flexible model such as TVA (Bundesen, 1990) could account for these findings because the contents of working memory could be used to set the appropriate bias terms to zero so attention would never be deployed to similar items.

One may question whether working memory representations are ever used to guide attention during visual search. However, several recent studies suggest that working memory may be crucial for efficient visual search when the identity of the target changes from trial to trial. In an elegant lesion study, Rossi, Harris, Bichot, Desimone, and Ungerleider (2001) had monkeys perform a visual search task in which the identity of the target changed frequently (i.e., every several trials) or infrequently (i.e., the target was the same for an entire day of search trials). The corpus callosum of each monkey was cut and essentially all prefrontal cortex aspirated from one hemisphere. By separating the hemispheres of the brain the researchers had the unlesioned hemisphere of the monkeys serve as a within subject control for the lesioned side. The prefrontal cortex is believed to be the part of the brain that implements working memory functions (e.g., Goldman-Rakic, 1996; Miller, 1999). Thus, stimuli presented to the lesioned hemisphere are

processed without the benefit of working memory mechanisms. However, they found that when the identity of the search target remained the same across many trials search efficiency was the same whether performed by the intact or lesioned hemisphere. In contrast, when the searched-for target changed frequently across trials the lesioned hemisphere performed search extremely inefficiently compared to the intact hemisphere. A behavioural study in which human observers concurrently performed a visual working memory task and visual search has yielded a similar pattern of results (Woodman, 2002). Concurrently maintaining information in visual working memory did not interfere with visual search when the identity of the target did not change across an entire block of trials, but interference occurred when the identity of the target was different on each trial.

In fact, even without a concurrent working memory load, search performance is markedly slower when target identity changes from trial to trial within blocks (Bravo & Nakayama, 1992). Two factors appear responsible. First, the need to reconfigure the visual system to search for a new target on each trial requires time (Di Lollo, Kawahara, Zuvic, & Visser, 2001; Kawahara, Zuvic, Enns, & Di Lollo, 2003). The findings described in the previous paragraph suggest that working memory plays a critical role in such reconfiguration. When the target does not switch within a block, observers may rely on long-term representations of the target. A second reason that search is faster when the target identity is constant is that when the same target feature repeats across trials, search benefits from feature priming. Maljkovic and Nakayama (1994, 1996, 2000) required subjects to discriminate the shape of the target that was a different colour than the distractors in the search array, commonly known as a *pop-out* search task. In addition, the specific colour of the target could change from trial to trial although it was always different from the colour of the distractors. They found that when the target was the same colour on consecutive trials subjects were faster at discriminating the target's shape. Moreover, this facilitation for target colour repetition lasted across several intervening trials. This effect, known as priming of pop-out, may reflect an implicit memory representation of the attended target. This memory representation causes attention mechanisms to select similar items and inhibit items that do not match it during a number of subsequent search trials. These memory representations significantly influence the efficiency of pop-out search for approximately 30 s regardless of whether subjects attempt to use them or not (Maljkovic & Nakayama, 1994), suggesting that the representations are maintained in a short-term implicit memory system. A related observation made by Müller and colleagues (Found & Müller, 1996; Krummenacher, Müller, & Heller, 2001; Müller, Heller, & Ziegler, 1995) is that observers are also faster to detect pop-out targets when they can predict along what feature dimension (e.g., colour or orientation) the target will differ from the distractors. This

suggests that priming of pop-out may spread within a feature dimension or that search can be facilitated by actively configuring the visual system to process features of the relevant dimension (e.g., Müller et al., 1995).

Thus, object working memory may be needed for reconfiguration when targets change from trial to trial, but not when observers may rely on long-term memory representations for targets that do not change within blocks. In contrast, the spatial selection mechanism that maintains spatial working memory representations appears to be necessary for all search tasks. The phenomenon of priming of pop-out shows that perceptual traces of attended targets facilitate search in subsequent trials. These findings provide a nice lead into the following section that will review many other demonstrations of how memory representations of both targets and distractors affect visual search from trial to trial.

LONG-TERM MEMORY AND SEARCH

Visual search can benefit from memory representations of previously attended targets as well as distractors. We begin by examining the evidence for the retention of target information across many trials, and then turn to the issue of whether information about the distractor objects is remembered across trials.

Is information about attended items stored in long-term memory across trials?

Whereas the working memory system is believed to be severely limited in its capacity to store information, long-term memory stores appear to be vast if not unlimited in capacity (Standing, 1973; Standing, Conezio, & Haber, 1970). Therefore, one might predict that an item that was attended during search would be remembered beyond the time of presentation. This is exactly the type of evidence that Hollingworth recently reported (2004). He required subjects to perform a dot-following task in which a dot was shifted between objects in a computer rendered scene followed by a memory probe at the end of the trial. The objects in the search array were small enough to require that they be foveated to be discriminated. He then tested subjects' recognition memory for an item that they foveated some number of fixations ago. He found that subjects could discriminate items that they had previously fixated during search from visually similar foils. Moreover, subjects' change-detection accuracy remained high, i.e., an A' of approximately .75, even when over 400 objects had been fixated between the fixation of the to-be-tested object and the testing event. Hollingworth obtained a similar type of result using a visual search task in which subjects previewed the search scene

before being cued as to what the target object would be on that trial. During both the preview and active search of the scene subjects' eye movements were recorded. Using this paradigm, he found that observers could fixate the target significantly faster if they had received a preview on that trial compared to those trials in which they did not. Surprisingly, this benefit was observed even when the target object had not appeared in the preview of the scene, although the size of the facilitation was reduced compared to when the target object was actually present. This suggests that subjects do not just remember the target location from the preview but that a representation of the contextual objects and surfaces is built up and stored in memory. These results suggest that the visual system accumulates information about the spatial layout and specific locations of objects in complex scenes. Similar conclusions were drawn by Castelhana and Henderson (2005), using a paradigm in which observers' memory for distractors was tested. Their subjects demonstrated above-chance recognition for the distractors even though they had only been attended in order to reject them as nontargets. In summary, these findings suggest that our memory for items that are fixated during search is quite robust even after processing a large number of other objects within the session (e.g., Hollingworth & Henderson, 2002).

In contrast to the conclusions drawn using these overt measures of selective processing, other approaches to this question have yielded the opposite conclusion. For example, one may try to have subjects commit a visual search array to memory by repeating the same display over many search trials to see how overlearning may affect the efficiency of search. This was the approach taken by Wolfe, Klempe, and Dahlen (2000) in a series of experiments. They required subjects to perform visual search in several conditions. In the repeated search condition subjects were shown exactly the same array for up to a thousand trials and were simply asked to search for a different target on each trial. In the comparison condition the visual search arrays were composed of randomly selected elements on each trial. Wolfe et al. predicted that if information about the search array accrues in long-term memory then across trials search should become increasingly efficient (i.e., exhibit shallower search slopes) in the repeated search condition relative to the condition in which a new search array was presented on each trial. However, the slopes of the search functions did not differ between conditions. These data suggest that subjects continue to perform visual search using the same visual strategies even though a more efficient memory search algorithm is available to them. The findings of Wolfe et al. are surprising given previous reports of increased search efficiency with practice (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Although the methods differed greatly, an explanation for the lack of learning in Wolfe et al.'s task is that they employed a variable mapping task in which the target changes from trial to trial, a task condition that leads to

inefficient learning, according to Shiffrin and Schneider. Nevertheless, the lack of benefit from repeated searches through the same display in Wolfe et al.'s study remains impressive.

Do memory representations of distractors influence search efficiency across trials?

Another approach for studying the relation between visual search and long-term memory is through the effects of learned semantic relatedness. Returning to Shiffrin and Schneider's studies (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977), they classically demonstrated that target recognition is facilitated if there is a consistent mapping (association) between the target and distractor set. In addition, Chun and Jiang (1999) showed that target detection was facilitated when the target shape always appeared together with the same set of distractor shapes, compared to a condition in which the target shape was not correlated with the background distractor shapes.

Real-world associations facilitate search as well. Recently, Moores, Laiti, and Chelazzi (2003) demonstrated that distractor objects that are semantically related to a searched-for target influence the speed and accuracy with which visual search can be performed. Although the presence of an object (e.g., a hammer) that is semantically related to the target being searched for (e.g., nails) did not significantly influence the speed and accuracy of finding the target when it was present, on target absent trials subjects were significantly more likely to respond incorrectly or slowly to an array that contained a related distractor than one that did not. Moores et al. propose that distractors that are semantically related to the target attract attention to themselves. Supporting this proposal, subjects were more likely to make a saccade to the related distractor than unrelated control items. Attention researchers have tended to study visual search using stimuli that lack strong semantic associations so that experimental results are easier to interpret. Nevertheless, the Moores et al. study shows that the inherent structure of long-term memory is likely to be ecologically important for everyday vision, which undoubtedly benefits from visual knowledge accumulated over the lifetime of an observer.

Although the study described above proposes that some distractors may attract attention to themselves based on their associations to targets in long-term memory, other research suggests that memory representations of ignored distractors can cause similar items to be processed less efficiently. For example, when observers discriminate the identity of a target word (or shape) superimposed upon a distractor word (or shape) of a different colour, target discrimination time is increased if that target was shown previously as

a distractor. This effect known as *negative priming* is commonly thought to result because the suppression of the distractor is necessary for target selection (DeSchepper & Treisman, 1996; Tipper, 1985). However, debate has raged over the time course of this effect (Neill & Valdes, 1992) and the underlying mechanism that causes it (Moore, 1996). The modal paradigm for studying negative priming involves presenting a single target and distractor that essentially share the same spatial location. Therefore, the processing demands differ significantly from visual search paradigms in which many distractors are distributed around a target with each occupying a unique location. Supporting this distinction is ample evidence that representations of distractor objects are stored in memory during search and that these representations have the opposite effect of facilitating search in familiar environments.

One way for our visual systems to find target objects more efficiently is for it to take advantage of statistical regularities present in the world that surrounds us. For example, if you could store a representation of the context in which you find a specific target object then you should be able to find the target more quickly the next time you encounter that same context. Recent studies have provided evidence for such learning of contextual information that serves to guide attention to embedded target items. Chun and Jiang (1998, 1999) had subjects perform a fairly demanding visual search task (e.g., a left or right rotated target “T” among rotated distractor “L”s) across many blocks of trials. During the first block of trials the subjects discriminated the identity of each target in randomly generated spatial configurations of distractor objects. However, on each subsequent block of trials, half of trials presented configurations of distractors that were repeated from the first block. The old, repeated display trials were interleaved with trials that presented new randomly generated spatial configurations of distractors. The target was always in the same location in these repeated configurations of distractors although the target identity, and therefore the required response, was not correlated with the presence of a specific configuration. As shown in Figure 2, Chun and Jiang (1998, 2003) found that subjects generally became faster at discriminating targets across blocks of trials. In addition to this general learning of the task, observers became even faster at discriminating targets embedded in repeated configurations relative to targets in the novel distractor configurations. Chun and Jiang (1998, 1999) termed this effect *contextual cueing* based on the idea that subjects’ memory representations of the repeated contexts of distractors were guiding attention to the target location.

The remarkable aspect of the learning that underlies contextual cueing is that it appears to occur implicitly. That is, although subjects become significantly faster at finding targets in repeated arrays compared to novel arrays they report being completely unaware that such repetitions occurred.

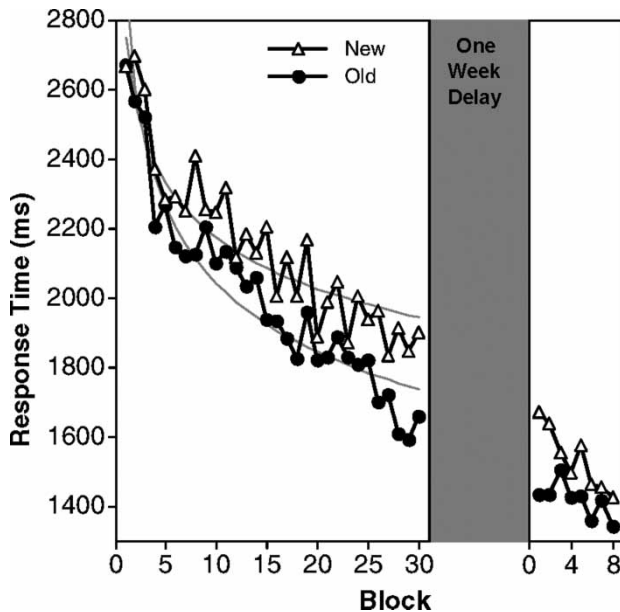


Figure 2. Targets appearing in repeated (old) scenes were detected more quickly than in new scenes. The learning persisted up to at least 1 week (Exp. 3, Chun & Jiang, 2003).

Moreover, the few participants who did report being aware that such repetitions were occurring produced contextual cueing effects of similar magnitude to those produced by subjects who were unaware of the repetitions (Chun & Jiang, 1998). When subjects were tested with an old–new forced-choice discrimination task following the visual search session, they were at chance at discriminating distractor contexts they had seen 30 times from novel displays they had never seen before. Other explicit tests of subjects' memory for the repeated contexts yielded similar results. For example, observers did not perform better than chance when shown the repeated configurations of distractors without the targets and required to choose the quadrant in each array that they believed should contain the target item (Chun & Jiang, 2003). In addition to the implicit nature of contextual learning, the representations of the learned distractor configurations appear to last a long time. Specifically, subjects who were retested on the visual search task 1 week after originally learning the set of repeated contexts were still significantly faster at searching for targets in the repeated contexts (see Figure 2) (Chun & Jiang, 2003). Finally, this type of implicit learning is not specific to spatial contexts of distractors but is also observed when target identity covaries with the identity of the distractors, when the trajectory of a moving target is predictable based on the trajectories of

the moving distractors (Chun & Jiang, 1999), and when the temporal position of a target is predictable from the temporal sequence of distractor stimuli shown in a RSVP paradigm (Olson & Chun, 2001).

Thus, our visual systems are extremely sensitive to statistical regularities that may be present in visual search arrays. This sensitivity to statistical relationships between stimuli not only facilitates visual search performance but also appears to be important for learning scene structure (Fiser & Aslin, 2001), visual event structure (Fiser & Aslin, 2002a, 2002b), as well as other types of learning, such as word boundary learning in infants (Saffran, Aslin, & Newport, 1996).

CONCLUSIONS

In this paper we reviewed theoretical proposals on the roles that memory representations play in the efficient processing of stimuli during search. After weighing the evidence we can draw two general conclusions regarding the relationship between memory and search.

The first is that working memory representations of targets might be essential in guiding attention only when the identity of the target changes frequently from trial-to-trial. Nearly every model of visual search makes explicit claims that visual working memory is required to find targets and reject distractors in any search task. However, recent findings suggest that object working memory is not required when subjects search for the same target across trials within a session. Subjects may rely on long-term representations of targets instead. When the target changes on each trial, however, object working memory is needed to update the target template representations. In contrast to the task-dependent effects of object working memory, spatial working memory is always required in visual search. It is likely that spatial working memory is used to tag distractor locations as attention shifts from one object to another until the target is detected. Existing visual search models require revision to incorporate the different roles of object working memory and spatial working memory.

Our second conclusion is that long-term memory representations of targets, distractors, and the relations between the two play a significant role in biasing how attention is deployed in visual search. Theories have typically ignored the role of long-term memory in order to focus on bottom-up visual factors and within-trial top-down effects. However, to increase the ecological validity of visual search, models must begin to articulate how long-term visual knowledge biases attention. We suggest that such knowledge derives from statistical learning of regularities that undeniably exist in the visual environment. Simply put, memory traces of attended targets and target contexts facilitate the viewing of similar scenes in future encounters.

We opened this review by stating that an advantage of the visual search task is that it appears to require minimal memory requirements. So it is ironic to see that the role of memory in visual search has become such a major focus of study and debate in modern research.

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