

## On the manifestations of memory in visual search

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Received 13 December 1999; revised 19 January 2000; accepted 27 March 2000

**Abstract**—Evidence is presented supporting the thesis that performance in visual search tasks is affected by the contribution of memory processes. Three levels of analysis, corresponding to the various time scales present in a typical search experiment, are discussed. Perceptual learning involves the task and stimulus specific improvement seen across blocks of training. Trial-to-trial priming has an influence which extends over 5–8 trials and lasts on the order of 30 s. Within-trial tagging prevents the re-inspection of already attended (or fixated) items. Also at the within-trial level of analysis, parallel accumulation of evidence for target presence/absence or target location inherently involves memory mechanisms. Organizing the various phenomena in this way makes it apparent that the various mechanisms may interact in a causal way. Within-trial tagging may contribute to priming which may contribute to perceptual learning. Recent proposals that visual search is memoryless (amnesic) are discussed and dismissed.

### 1. INTRODUCTION

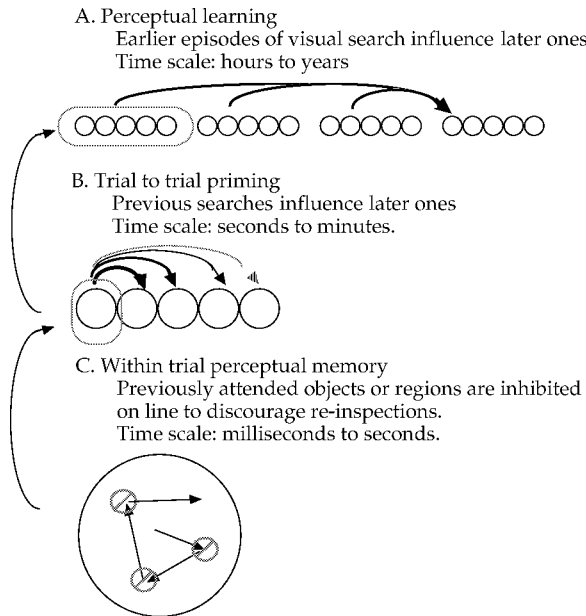
Attention and memory form an interactive and iterative network (c.f. Miyashita, 1993; Cowan, 1995; Desimone and Duncan, 1995). Explicit memory is influenced, and perhaps determined, by the focus of attention (James, 1890; O'Regan, 1992) while that same focus can be oriented based on previous experience and established schemata. Current studies of cognitive neuroscience and brain imaging are repeatedly showing us that behavior and awareness depend on an elaborate network of processing centers operating in concert with one another to perform the functions we label as memory and attention. In this context, it is not surprising that visual scanning and searching involves a number of different types of memory each contributing to efficient and orderly search behavior. What is surprising, however, is

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that besides the few exceptions noted below, the literatures on memory and visual search are for the most part non-overlapping. Several theorists of visual search (e.g. Treisman and Gelade, 1980; Duncan and Humphreys, 1989; Wolfe, 1994) incorporate memory mechanisms in their models, but usually they are not explicit about the type of memory or the specific role that it plays. Hence, one purpose of the present paper is to make the linkages between memory and search explicit by briefly describing and organizing germane examples of empirical research that illustrate the roles of memory in visual search. Our broader goal is to lay out a framework for understanding the different contributions that memory can make to orderly searching behavior, both in the laboratory and in the real world.

The reviewed literature is organized around three different time scales involved in a typical search experiment (see Fig. 1). At the broadest time scale are examples of perceptual learning which have been in the literature for over two decades (c.f.



**Figure 1.** A schematic diagram of the three different time scales discussed in the review. (A) the broadest time scale involving perceptual learning across blocks of trials. The improvements seen can be both task and stimulus specific and can last for over one year. Each circle represents a single trial organized into blocks and the arrows indicate the effect of one block on blocks in the future. (B) Trial-to-trial priming which appears to last around 30 s, or 5–7 trials in a typical search experiment. Again, each circle represents a trial and the gradually fading arrows indicate that effects are strongest on the next trial and diminish across trials. (C) Within-trial tagging of distractor items which reduces the likelihood of re-examining items. The large circle indicates that processing is within a single trial. The arrows represent the movement of attention or the eyes and the circles with the lines through them represent the inhibitory tags assigned to attended (or fixated) items. The arrows on the left side of the figure make explicit the proposal that the on-line processing which occurs within a trial may contribute to the between-trial priming reported in (B) and that this priming may also contribute to the perceptual learning involved across blocks of trials (A).

Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977) and which indicate that the processing of the stimuli being examined and the task being performed become more automatic with each passing trial (see Shiffrin and Schneider, 1984; Shiffrin, 1988, for reviews). A shorter acting form of memory can be seen in the finding of trial-to-trial priming which aids the detection of repeated targets and interferes with the visual grasping of items that were previously distractors (e.g. Maljkovic and Nakayama, 1994; Maljkovic and Nakayama, 1996; for an earlier example see Rabbitt *et al.*, 1979a). Finally, within a given trial, two forms of memory appear to be operating: one tags previously scanned items to avoid re-inspections (Klein, 1988) while the other accumulates evidence for or against the presence of a target in parallel across the array (e.g. Townsend, 1974; Ratcliff, 1978; Broadbent, 1987). We believe that serial scanning (of individual items or groupings) and parallel accumulation across the visible portion of the array proceed simultaneously. Possibly under the strategic control of the searcher, the outputs of these isolable subsystems may be differentially weighted and performance may be based on a competitive (horse race) or cooperative (integration) interaction. Each of these forms of memory — perceptual learning, trial-to-trial priming, and perceptual memory — will be discussed briefly and examples are presented in order to reinforce the thesis that memory operates in visual search in many different ways.

Before beginning this enterprise, it behooves us to briefly explore the relation between explicit and implicit memory (Schacter *et al.*, 1993). Explicit memory refers to our ability to consciously recollect an episode, fact, or action which we have experienced in the past. Inherent in its definition is the knowledge that we are remembering a previous event. In contrast, implicit memory consists of the countless automatic and uneventful aspects of our everyday lives, which are affected by previous experience without our necessarily linking the present episode to the past learning environment. The dissociation between these two forms of memory has a robust history (Schacter, 1995; Verfaellie and Keane, 1997). Some have proposed that these two aspects of memory form unique and separable systems of cognitive processing instantiated in different neural structures. We do not wish to argue this point, but only to emphasize that there is a difference and move on.

The literature is replete with examples of double dissociations and manipulations that isolate each type of memory. The role of explicit memory in visual search is less of a concern for present purposes as it falls into the area of research dealing with response tendencies and cognitive strategies which, while very interesting, are outside the purview of typical research on visual search. Of course, the subject must remember what the target is, what the appropriate response is, and how to do the task. These memories, however, are not the topic of the present work, which focuses instead on examples of implicit learning and memory that influence our searching behavior without the need for intrusion from our conscious selves. There is also a literature on the role of expectations in the conjoining of features (c.f. Treisman and Gelade, 1980; Treisman and Schmidt, 1982) which will not be discussed in this review.

In order to provide a context, let us consider an example of real life search — the task of collecting your child from daycare. To complicate the situation, she (along with her friends) is usually moving about and is never in the same place from day to day. This is truly a dynamic search condition. As you search, you presumably will avoid revisiting rooms you have already searched until all of the rooms have been explored — a form of online tagging. On subsequent days, you may begin where you found your child on the previous day (a form of trial-to-trial priming). As the visits continue, you should quickly discover your child's favorite hideouts and your search would become more and more efficient (a form of perceptual learning).

## **2. PERCEPTUAL LEARNING**

Perceptual learning pervades our everyday lives and aids in most tasks we are required to complete repetitively. Over a century ago, James (1890) noted that wine tasters and fabric merchants develop task-appropriate skills, which far surpass that of the non-expert. Later, Hebb (1949) and more recently Eleanor Gibson (1969) emphasized the important role of perceptual learning in both the developing infant and the mature adult. Although learning during infancy is to be expected, it is often assumed that low-level processing systems show reduced plasticity and became rigid in their functioning with development. There are demonstrations, however, that contradict this assumption; for example, the sensitivity of a peripheral sense (e.g. touch on the back) can be increased by 100 times within a few weeks of practice (Gibson, 1969).

In the context of search there are a number of studies showing that both task-specific and stimulus-specific skills are being learned and retained for long intervals (e.g. Fisk and Hodge, 1992, tested performance after one year). Early work (e.g. Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977; see Shiffrin, 1988, for a review) focused on two forms of search — memory search and visual search. In memory search, the observer is given a list of items to memorize and is then presented with a single item and asked if it was present in the list. Visual search is somewhat complementary to this in that the observer is typically given a single item to memorize and is then presented with an array of items and asked if the target is in this set. Although these two tasks are often considered to be tapping similar mechanisms, a dissociation between the two tasks has recently been shown (Hillstrom and Logan, 1998), with visual search requiring at least one unique set of visual prioritization processes (c.f. Wolfe, 1994). Hybrid memory/visual search appears to be different from either of the pure forms. In this task, the observer is given a variable number of targets to search for in displays which vary in the number of items. Typically, search performance is determined by an interaction of the two numbers (number of targets in memory and number of distractors in the display). Fisk and Hodge (1992) showed that, after a one-year retention interval, performance in pure memory search when the same three items at training were used at test was undiminished from pre-interval levels. For pure visual search,

there was a small decline in performance after the one-year interval with the trained items. In the hybrid condition, there was a very large decline in performance (i.e. forgetting) after the same interval. The forgetting in visual and hybrid search was attributed 'to the need for extremely fine perceptual tuning' (Fisk and Hodge, 1992, p. 161). This conclusion is strongly supported by a recent demonstration (Ahissar and Hochstein, 1997) that detection of an orientation singleton is dramatically improved with practice. In this study, the observer simply reported if an oddly oriented element was present in a fairly dense array of line segments. Performance improved across the first 100 or so trials, followed by a more gradual improvement over the next 1000 trials. Consistent with Fisk and Hodge (1992), Ahissar and Hochstein (1997) found that the degree of transfer to a novel set of stimuli was determined by the difficulty of the original discrimination. With an easy task, there was a great deal of transfer whereas with a difficult task (only 16 deg difference from the distractors) there was virtually no transfer. These effects are so striking that even a single 'easy' trial can produce significant transfer to a more difficult task whereas without this easy task, some subjects never improved above chance! Thus, it seems that the degree of stimulus-specific perceptual learning is related to the difficulty of the search task with more difficult discriminations producing highly specific learning. This may be related to the increased need for attention in the more demanding task.

Compelling evidence for stimulus-specific memory in search paradigms comes from a comparison of consistent mapping (CM) and variable mapping (VM) conditions (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977). In CM, the identities of the targets and distractors remain constant across blocks of trials, whereas with VM either the target or distractor changes identity from one trial to the next. Search performance in the CM condition is consistently superior to that found in the VM condition strongly supporting the claim that memory for the items in the CM condition was aiding performance. Of course there was improvement in the VM condition which can be attributed to task-specific learning. The more interesting item-specific learning can involve attributes of the target, the distractors, or both. Ahissar and Hochstein's (1997) finding (described above) indicates that target-specific knowledge can improve search. Distractor-specific learning is illustrated in recent studies by Lubow and Kaplan (1997) and Flowers and Smith (1998). Flowers and Smith (1998), for example, manipulated the degree to which distractor identities were correlated with the presence *vs.* absence of a target. While subjects were unaware of them, these contingencies were implicitly acquired, as demonstrated by the finding that performance deteriorated significantly when they were reversed in the final block of trials. Lubow and Kaplan (1997) demonstrated that repeated search with a single distractor shape in the first phase of an experiment led to much slower searching when this item became the target in a later phase. This learning was attributed to latent inhibition (Lubow and Moore, 1959; see Lubow, 1973; Lubow, 1989, for reviews), a well-established effect in the animal learning literature wherein stimuli that are passively pre-exposed (i.e. presented without

reward) take many more trials to enter into an association in a later phase of learning than those which are not. Whatever the theoretical interpretation, the finding that previous distractors make poor targets provides compelling evidence that memory for distractor identity contributes to search performance.

A series of experiments by Chun and Jiang (1998, 1999; for a review see Chun, 2000) shows that repeating the context in which a target is found can dramatically speed search performance. In one study (Chun and Jiang, 1998) observers searched for a rotated T among rotated Ls. In each block of 24 trials there were 12 novel configurations of the items and 12 configurations where the locations of items were held constant across blocks. These so called 'old' displays were presented once per block. Reaction times on these 'old' displays were faster than on the new displays even after only five blocks of trials (i.e. 5 repetitions). It was concluded that observers have a memory trace for the previously presented configurations which, once recognized, aid in target detection. In further studies Chun and Jiang, 1999, vertically symmetrical targets were the targets among distractors with different orientations of symmetry. The exact location of the items could be varied across trials, but on CM trials, a given target shape was paired with the same set of distractor identities. There were eight different CM trials in a block and eight VM trials where a random assortment of distractors was paired with different targets. After a single epoch (four blocks) there was a sizeable advantage for CM trials compared to VM trials indicating that observers used the identity of the distractors to help find the target which is in an unknown location. In a final study (Chun and Jiang, 1999), the items moved dynamically throughout the search display. On CM trials (six unique instances per block), the trajectory of the target and distractors was perfectly correlated. On VM trials (six per block), there was no relation between the path taken by the target and distractors. Again, search performance was faster on CM than VM trials. Note that the form of memory involved in enabling this enhanced performance is complex, involving the relative motions of the target and distractors.

Within the context of searching for your child at the daycare, this form of memory may play an important role — your child may prefer to play with the same children or toys across days. Acquiring this knowledge requires time and experience; once acquired, the result will be more efficient search performance.

In this section, we have highlighted examples which show that memory operates in search at several different levels including task-specific learning (relative improvement in VM search conditions), target-specific memory (Ahissar and Hochstein, 1997), distractor-specific memory (Lubow and Kaplan, 1997; Flowers and Smith, 1998) and context-specific memory (Chun and Jiang, 1998, 1999).

### **3. TRIAL-TO-TRIAL PRIMING**

The next time scale to be considered is that between trials. Each trial in a search experiment sets up a memorial trace which contributes to the perceptual learning

discussed above (c.f. Logan, 1988) and affects performance in the following few trials. As we will see, target and distractor identities and locations can all affect subsequent performance when these attributes are repeated.

Maljkovic and Nakayama (1994, 1996, 2000); McPeck *et al.* (1999) have demonstrated that repetition of a previous trial's target identity, target location, distractor identity or distractor location can all influence search performance. In one study (McPeck *et al.*, 1999) observers searched for an odd-colored diamond and indicated whether the right or left side had been truncated. The singleton nature of the target ensures that attention will be effortlessly oriented (Treisman and Gelade, 1980) while the fine-detailed nature of the task requires such orienting (c.f. Bravo and Nakayama, 1992). Repetition of the color of the target led to significant improvement in search performance. This facilitation lasted between 5 and 7 trials (about 30 s) and showed a monotonic decay in this interval. Moreover, explicit knowledge of the upcoming color did not influence the magnitude of the facilitation, nor did vocal rehearsal of such knowledge. Finally, this effect was undiminished by presentation of successive targets to opposite eyes. This pattern suggests that it is the cognitive act of finding a singleton that benefits from the prior performance of the same act. This target facilitation was also observed when the required response was a saccade as opposed to a target discrimination (McPeck *et al.*, 1999) indicating the robust nature of the priming effect (see also Hillstrom, 2000).

With regard to item location, Maljkovic and Nakayama (1996) demonstrated that presenting a target in the same position as a target in a previous trial (1-7 back) produced a facilitation in responding that was largest in the 2-back position and decreased monotonically beyond this. The observation that immediate location repetitions (the 1-back position) did not show the largest facilitation was attributed to the additive effects of target facilitation and inhibition of return (Posner and Cohen, 1984; see description below). When the target was presented in a location previously occupied by a distractor, search performance was hindered. This effect was completely additive (in terms of search times) with the identity priming effect discussed above, indicating, perhaps, that facilitation/inhibition may be applied concurrently at different levels of processing. Consistent with the distractor inhibition finding, Horowitz (1995) presented a detailed examination of this effect using a feature search for diagonal bars among horizontal bars. One interesting finding was that presenting a distractor at the same location across several trials led to an increase in the relative inhibition when a target was finally presented at this location. This accumulation of inhibition continued across five trials (the maximum tested by Horowitz). This cumulative inhibition was attributed to a negative priming-like effect — a decrement in performance when targets share properties with previously ignored distractors (see Fox, 1995, for a review). The specific form of negative priming that might be thought to be operating in Horowitz's study, was originally reported by Tipper *et al.* (1990) and has been called negative priming for spatial location (see also Houghton *et al.*, 1996). In this case, targets are identified on the basis of a non-spatial attribute (shape or color) and it is their location that is

reported. There is a delay in localizing targets presented in immediately preceding distractor locations. It has recently been noted (Christie and Klein, 2000) that most previous studies of negative priming for spatial location have used an unbalanced design wherein the locations of the probe's target and distractor can be predicted from the arrangement on the prime display. Christie and Klein (2000) demonstrated that when a completely balanced design is used, the same delay is observed when a target is presented in the location of a previous target. On this basis, Christie and Klein (2000) have proposed that negative priming for spatial location is due, not to distractor inhibition, but to inhibition of return (IOR, see next section), which would act similarly on previous targets and distractors, so long as both are attended in the prime display, or to IOR's flip-side, a new object advantage. Whether IOR, negative priming, or object files, or some combination, is used to explain the effects of previously searched arrays on current performance, there is no doubt that some form of memory is involved. A similar conclusion has been reached by Milliken and colleagues (Milliken *et al.*, 2000).

Many, if not all, of these effects have historical antecedents which appear to have been lost to the literature. Rabbitt *et al.* (1977, 1979a, b) demonstrated very similar phenomena using letter stimuli. When the background of distractor identities was repeated, or the target's identity or location was repeated, faster search performance was observed. This effect was examined across three trials and found to diminish slightly, but to still be evident. The fact that similar findings have been observed with very different stimuli (letters, sawed-off diamonds, and oriented bars) demonstrates that this is a ubiquitous result that should be examined in relation to the perceptual learning results discussed above. Specifically, it is possible that this short-lived priming effect contributes to the longer lasting memory which accrues across blocks of trials (indicated by upward arrows in Fig. 1).

In our real-life example, information gathered on one day should improve the efficiency of search on the subsequent day. However, it is true that many of the other demonstrations, discussed above, are difficult to import into the daycare example, we believe that with sufficient imagination each one can be shown to be operating in ecologically valid situations such as searching for a tumour in an X-ray (c.f. Krupinski, 1996; Trillo *et al.*, 1997).

#### **4. WITHIN TRIAL MEMORY OF PREVIOUS ORIENTING (OVERT AND COVERT)**

Before outlining the arguments which have been presented for within trial memory of previous orienting, it is important to outline two possible models of visual search and how memory plays a role in each. Serial search models (Treisman and Gelade, 1980; Treisman and Gormican, 1988; Wolfe *et al.*, 1989; Treisman and Sato, 1990; Wolfe, 1994) propose that visual search is accomplished by the serial inspection (either covert or overt) of items in the scene until the target is found. That is, attention (or the eyes) moves from item to item discarding distractors, in an effort to



find and respond appropriately to the target. For this type of search to be reasonably efficient, some form of memorial representation that can prevent or discourage the re-inspection of items is needed. We will see below, that in most arguments for or against the role of memory in search, this is the type of model that has been assumed. However, a second class of model has also been proposed which postulates a search mechanism that operates by accumulating evidence for the presence of the target in parallel across the visual scene (Townsend, 1974; Ratcliff, 1978; Broadbent, 1987; Duncan and Humphreys, 1989; Humphreys and Müller, 1993). The operation of memory in this form of model is inherent in the design of the system. That is, in order to accumulate information over time, the information must be accumulated in something, a memory store of some sort. The exact form of this storage depends on the model in question. Those authors who refute a role for memory in visual search (e.g. Horowitz and Wolfe, 1998; Wolfe *et al.*, 1999) have typically not considered this form of memory. Likewise, we will not spend more time discussing this form of memory other than to say that search behavior is likely mediated by both serial and parallel mechanisms. Indeed, a comprehensive understanding of visual search is not likely to follow from efforts to determine which model is right. Progress will flow instead from an acknowledgement that both are right and an effort to determine when they operate and how they interact.

In relation to serial models, the need for and existence of a mechanism to prevent re-inspections was initially only implied. In serial self-terminating search, each display item is examined once and only once to determine if it is the target or a distractor. On a target present trial, it is noted that this strategy will find the target after, on average, half the items have been inspected; whereas on target absent trials, each item must be inspected to permit a confident 'target absent' response. In early statements of this model (e.g. Treisman and Gelade, 1980), the prevention of re-inspections was assumed to be accomplished with perfect efficiency, but no explicit mechanism was described for doing so. A mechanism that could serve this purpose was discovered in 1984, by Posner and Cohen, and was subsequently called inhibition of return (IOR). Exogenous orienting (overt or covert) toward a peripheral stimulus usually improves the extraction of information in the vicinity of the attended item. However, once attention or gaze is relocated away from it, there is deterioration in performance in the previously attended region. From this deterioration it has been inferred that re-orienting toward previously attended locations is inhibited (Posner and Cohen, 1984; see Klein, 2000; Taylor and Klein, 1998, for reviews).

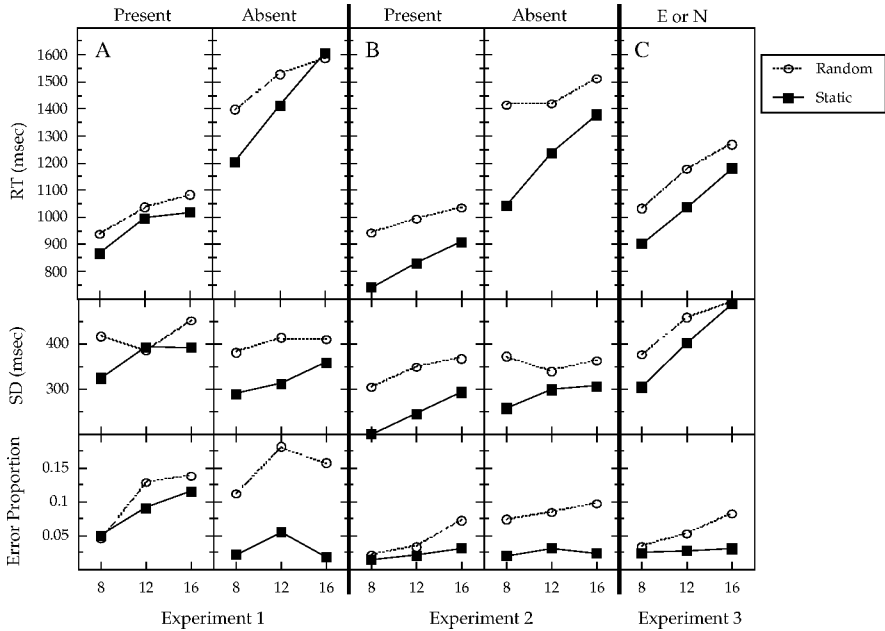
Following the lead of Posner and Cohen (1984), Klein (1988) proposed that IOR facilitates visual search for 'hard-to-find' targets (those which do not pop-out, and hence might require a serial inspection of the search array) by tagging locations that had been inspected by attention. Such inhibitory tagging of display items that have already been examined attentively would, by repelling attention, help the observer avoid re-inspecting them. Such a proposal requires that IOR can be maintained at multiple locations. Although this possibility was briefly disputed (Pratt and Abrams,

1995; Abrams and Pratt, 1996) it has since been amply demonstrated by Tipper *et al.* (1996) and Kingstone and colleagues (Danziger *et al.*, 1998; Snyder and Kingstone, 2000).

Klein (1988) tested this functional explanation of IOR by presenting luminance-detection probes immediately after the subject had performed an easy (pre-attentive; target pops out) or difficult (requiring serial allocation of attention to array items) visual search. By hypothesis, in the easy search task, the target pops out, and therefore there would be no need for inhibitory tags. In contrast, in the difficult search task it is assumed that attention or gaze moves from distractor to distractor until the target is found, and following Klein's extension of Posner and Cohen's proposal each re-orientation should be accompanied by IOR. The pattern of results obtained by Klein was consistent with his proposal. In reconfirming a role for IOR as a search facilitator several recent studies (Klein and MacInnes, 1999; Takeda and Yagi, 2000; Müller and von Mühlelen, 2000) have demonstrated the importance of maintaining the search array when probing for the inhibition. This finding may help explain two early non-replications of Klein (1988) (Pontefract and Klein, 1988, as reported in Klein and Taylor, 1994; Wolfe and Pokorny, 1990) because in these studies the array was removed before the probe was presented.

Indeed, the observation of IOR following a serial search only if the search array remains present is precisely what would be expected from ecological consideration of the functional role attributed to IOR by Klein (see also, Tipper *et al.*, 1994). If IOR evolved to make search more efficient by inhibiting re-orienting toward previously inspected locations or objects, then it would be dysfunctional for the inhibition to continue when a new environment is encountered. One might expect that a complete scene change would clear the memory system responsible for storing IOR. Similarly, for IOR to be functional in real-world search it should be tagged to environmental locations in static displays and to objects in a dynamic scene. Both these properties have been confirmed (for environmental coding: Posner and Cohen, 1984; Maylor and Hockey, 1985; for object coding: Abrams and Dobkin, 1994; Tipper *et al.*, 1994).

Despite this line of research, Horowitz and Wolfe (1998) have recently claimed that visual search has no such form of memory or indeed any form of memory. Their evidence stems from a set of experiments comparing the typical static search condition with one in which the items in the scene are relocated every 100 or so milliseconds. That is, while the observer is looking for the target, the items being searched are removed from the screen and replaced in new locations. For Horowitz and Wolfe (1998), the critical finding is that search efficiency, as indexed by the RT search slopes on target present trials, appeared to be the same in these two conditions. They concluded that 'the visual system does not accumulate information about object identity over time (p. 577)' and further 'that visual search processes ... act on neural representations that are continually rewritten and have no permanent existence beyond the time span of visual persistence (p. 575)'. The logic underlying this conclusion depends on the fact that in the dynamic condition,



**Figure 2.** Mean correct reaction time (RT, top panels), within subject standard deviations of correct RT (middle panels) and proportion of errors (bottom panels) in each of three experiments (Panels A, B, and C show data from Experiments 1, 2, and 3 respectively) from Horowitz and Wolfe (1998). The task in Experiments 1 and 2 was to decide if the target (rotated T) was present or absent (side by side panels) in a field of rotated Ls. For experiment 3, the task was to decide which of two targets (N or E) was presented. The main manipulation of interest was whether the stimuli remained stationary across the trial (static) or were relocated every 111 ms (random). Support for the amnesic claim comes from the similarity in RT search slopes for the target present trials. Evidence of different strategies and efficiencies can be seen in the differences evident in the target absent data, pattern of standard deviations and the differences in accuracy across the two tasks. We thank Todd Horowitz and Jeremy Wolfe for their speedy cooperation in making these data available to us.

no location-specific tagging mechanism is possible, hence the similarity in slopes (proxy for search efficiency) led Horowitz and Wolfe to conclude that such a memorial tagging system must not be operating in the static condition. This conclusion can be challenged on a number of grounds. First, the full pattern of performance obtained by Horowitz and Wolfe (1998) in the static and dynamic search conditions (see Fig. 2) provides little support for their controversial proposal that search has no memory. Horowitz and Wolfe's conclusion depends on two premises that are not supported by aspects of their findings. These premises are that: (1) the same strategy is used in the static and dynamic search conditions, and (2) search efficiency is equivalent in the two conditions. The RT, standard deviation of RT and errors as a function of set size from each of Horowitz and Wolfe's (1998) three experiments are shown in Fig. 2. Note that the pattern with each of these dependent variables differed substantially between these two conditions. This is precisely the kind of evidence from which different strategies might be inferred to

be operating in the static and dynamic conditions. Additionally, note that errors were much higher, particularly at the larger set sizes, in the dynamic condition, thus providing compelling evidence that search was not equally efficient in the two conditions. A more detailed analysis of this study is available from the authors (Klein *et al.*, 2000). Additionally, Horowitz and Wolfe addressed the accuracy difference on their web page (<http://or.psychology.dal.ca/~dshore/hw.html>) and concluded that the absence of an efficiency advantage for the static condition cannot be explained by the accuracy difference we emphasize here. In our commentary we disagree and suggest that this is a classic example of an untoward speed-accuracy tradeoff (Wicklegren, 1977).

Second, at least one study has failed to replicate the RT pattern reported by Horowitz and Wolfe (1998). Olds *et al.* (1999) used a color detection search task with either static or dynamic displays (similar to those used by Horowitz and Wolfe, 1998), and obtained clear slope differences. Similarly, Kristjánsson (2000) found slope differences between these two conditions using larger set sizes. Even more supportive of a role for inhibitory tagging in search, he observed a clear decrement in search efficiency in the dynamic condition when the target was placed in a location previously occupied by a distractor. Third, even if the pattern is replicated, it may partially be due to a new object advantage in the dynamic condition. Khurana *et al.* (1999), Scheier *et al.* (1999) have shown that if each item is masked locally, a similar pattern to that observed by Horowitz and Wolfe (1998) is obtained; whereas if a global mask is used, there are clear slope differences favoring the static display. The global mask puts the static and dynamic conditions on a level playing field by eliminating any new object advantage in the dynamic condition.

Finally, the force of their argument rests on the lack of a difference in search slope function across the two conditions. If true (and not compromised by significant differences in accuracy), this is an interesting finding. However, it is not compelling evidence that the same processes are involved in the two searches. This point was made forcefully by Joseph *et al.* (1999) who demonstrated that visual search through an identical display five times led to the same slope each time (something quite similar to this has also been demonstrated by Wolfe *et al.*, 2000).

It is interesting to note that the role of memory in visual search has been explicitly explored in a computational model (Arani *et al.*, 1984) in the real-world context of searching for faults in a cement wall. They described a mathematical model wherein the amount of memory allocated to keep track of previous search results so as to avoid re-inspections was varied. They concluded that a model without memory could not account for the data available and that some mechanism that prevented re-inspections must be operating (though not at 100% efficiency). There are a variety of specific tasks that might be classified into the search category for which accurate performance critically depends on an explicit effort to remember. Tracking of multiple objects in dynamic displays (Pylyshyn and Storm, 1988) and the counting of targets in static arrays (Trick and Pylyshyn, 1994) are two examples. Although these are not traditional search tasks, it is undeniable that item-specific

memory must be operating in order to count or track the targets in these tasks. As such, these lines of research provide face validity to the claim that memory can operate in visual search. For additional recent evidence for memory in visual search see Peterson *et al.* (2000).

The laboratory task of searching for a target which is constantly moving and being relocated (c.f. Horowitz and Wolfe, 1998; Chun and Jiang, 1999; Khurana *et al.*, 1999) is clearly related to the task of identifying your child from among the other children running around in a room. As each object moves about, it is necessary that any inhibitory tag (c.f. Klein, 1988) move with them (c.f. Tipper *et al.*, 1994). Preventing re-inspections by such a mechanism will clearly improve the chances of quickly finding your little one.

## 5. CLOSING REMARKS

Despite recent claims to the contrary, memory clearly operates in visual search at a number of levels. An important empirical question concerns how these levels interact (see Fig. 1). For example, is the IOR seen within a trial (Klein, 1988) related to the distractor inhibition observed between trials (Rabbitt *et al.*, 1979a; Horowitz, 1995; Maljkovic and Nakayama, 1996)? The latter may simply be the accumulation of inhibition from within-trial processes. The same may be said about the observations of perceptual learning. The inhibition noted between trials may combine to produce some of the benefits that accrue over blocks when consistent mappings are used. In this context, it is important to consider the results of Lubow and Kaplan (1997) in light of the Horowitz (1995) findings. The first result was cast in the theoretical framework of latent inhibition (the reduction in associability of passively pre-exposed distractors) while the second result derives from consideration of negative priming (ignored distractors later take longer to identify) or inhibition of return (inhibited orienting toward previously attended locations). Although these two areas of research (conditioning and priming) are not typically juxtaposed, we believe that they should be. We also urge researchers to make the often hidden assumptions about how memory contributes to search explicit. That is, when considering how we search through our environment, the mechanism(s) whereby information is maintained throughout the search episode needs to be explicitly modeled and brought into focus. Finally, it is reassuring that so many memory mechanisms contribute to search behavior to allow the successful collection of my child from daily daycare.

### *Acknowledgements*

We would like to thank the faculty of graduate studies at Dalhousie University for travel support to the first author in order to attend the meeting of the Applied Vision Association in March of 1999 where these ideas were first presented. Also to the Killam Trust Funds for supporting the first author during his Post-doctoral fellowship and to NSERC of Canada for operating grants to the second author.

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