A LOOK AT LEARNING IN REPEATED SEARCH: THE ROLE OF MEMORY AND COMPETITION

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DEDICATION

While a number of people have contributed to my academic success, I would be amiss without acknowledging the two individuals without whom this dissertation would have never been written, my parents, Bob and Connie Skow. They may not know the intricacies of theories on visual search or even how to run an ANOVA, but they instilled in me a love of learning that, I am certain, will follow me throughout this life. They supported and encouraged me even on days, and yes, there were days, when I wanted to give up. Finally, I would like to thank them for reminding me *ad nauseam* that though our possessions in this world are transient, there are lots of intangibles, like education, that no one can ever take away from you.

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ABSTRACT

The role of memory in repeated search tasks is contentious. Wolfe et al. (2000) have argued that participants do not learn a repeated scene and continue to perform a time-consuming search process for hundreds of trials. In contrast, Chun and Jiang (1998, 1999) have shown that search efficiency is improved for repeated versus new scenes and this learning can occur for either spatial layout independent of identity or identity independent of spatial layout. The experiments presented here demonstrate that participants learn a great deal about repeated search displays including the location of a particular item (both identity and location), the relative probability with which an item occurs in a location, and direction from the fixation point to the target. I argue that memory is established for these components and the reactivation of these memories by a repeated search display produces competition. This competitive target verification process takes time and can result in positive search slopes, which have been taken as evidence for memory-free search – a flawed logical argument.

1. INTRODUCTION

Visual perception seems so effortless and immediate that at first blush, it is difficult to comprehend how complex the processes are underlying it. Questions, such as, how do human beings explore a stable visual environment, what are the mechanisms that help us extract information from a repeated scene, and what information is learned in a recurring context still need to be answered. Much focus has recently been given to examining the extent to which human beings process and remember a visual scene. Research has found that the gist of a scene can be extracted quickly and reliably (e.g. Potter, 1976), but the human visual system can be also be remarkably limited, for instance, in detecting changes in a visual scene (e.g. Simons & Levin, 1998). Recently, the role of memory in a visual search task has become contentious (e.g. Chun & Jiang, 1998; Gibson, Li, Skow, Salvagni, & Cooke, 2000; Horowitz & Wolfe, 1998; Kristjansson, 2000; Peterson, Kramer, Wang, Irwin, & McCarley, 2001; Takeda, 2004; Wolfe, Klempen, & Dahlen, 2000). In what follows I will first define what I mean by visual search and then review the controversy surrounding the role of memory in a visual search task.

In a visual search task participants are asked to report the presence or absence of a target item among some number of distractor items. Historically two types of search behavior have been investigated: efficient and inefficient. In efficient search the target and distractors are visually dissimilar and as a result the target appears to “pop-out” of the display. Reaction times (RTs) to report the presence or absence of the target do not increase systematically with increases in the number of display items because the target, if present, can be located quickly. In contrast, in inefficient search the target and distractors are perceptually similar. As a result RTs to report the presence of the target increase as the number of display items increase (e.g. Duncan & Humphreys, 1989; Treisman & Gormican, 1988). When using a visual search paradigm, researchers often examine search slopes as a way to understand their data. Search slope is defined as the change in RTs to report target presence or absence as a function of the number of items in the display. In efficient search, slopes are typically zero or near zero (i.e. less than 10 ms), whereas in inefficient search slopes are significantly greater than zero, typically greater than 20 ms per item (Wolfe, 1998).

1.1 Memory in Visual Search

Wolfe, Klempen, and Dahlen (2000) claimed that even when participants have been trained on the same visual search display for hundreds of trials they rely on vision not memory to verify target presence or absence. Participants were shown a visual display consisting of letters that remained in view throughout a block of trials. A probe which indicated which letter was the target on a given trial was presented at the center of the display. Each item in the display was probed as a target an equal number of times (see Figures 1 & 2). RTs to confirm target presence increased with the number of items in the display (2, 3, 5, or 8) indicative of inefficient search behavior. Wolfe et al. interpreted these results as evidence that participants continued to search through the display to locate the target as though they did not remember where it was. They reasoned that if

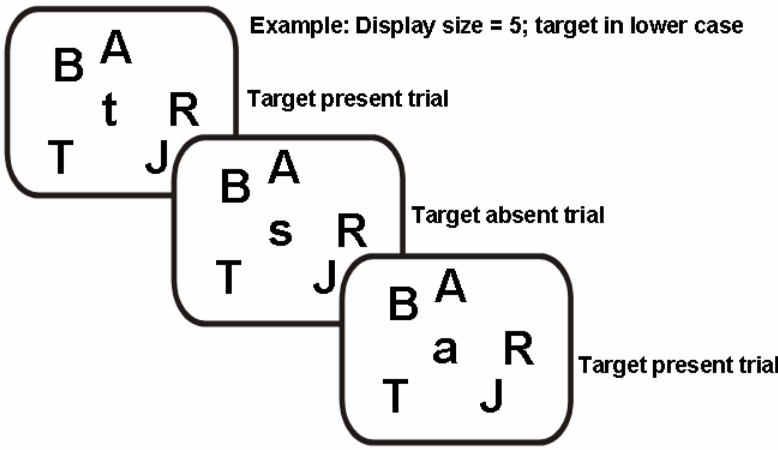

Figure 1. Example of a series of displays used by Wolfe et al. (2000) depicting a set size of five items. Participants were asked to report whether the target probe presented in lower case lettering at the center of the display was present among the uppercase letters presented around the imaginary circle. The top panel illustrates a target present trial. The lower case “t” presented at the center of the display is the probe. An uppercase “T” is present in the display at approximately the 7 o’clock position. The middle panel illustrates a target absent trial. An uppercase version of the target probe “s” is not present in the search array. Finally, the bottom panel illustrates another example of a target present trial in which there is an uppercase version of the target “a” probe in the display. Participants were queried about all five items in the display an equal number of times.

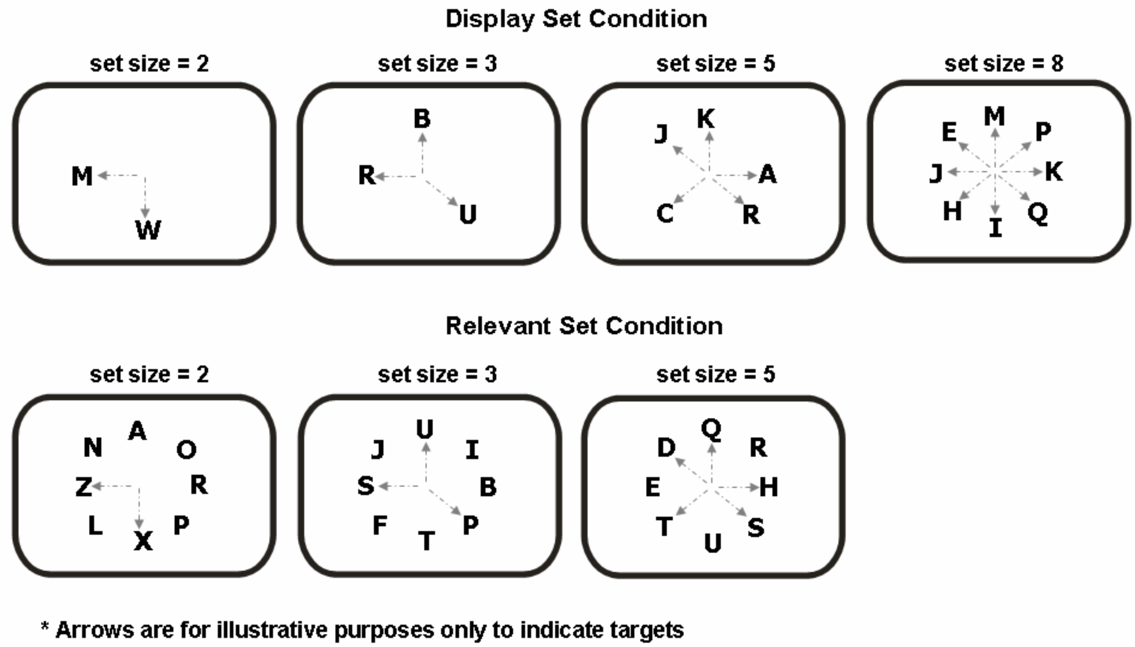

Figure 2. The top panel depicts the display set condition for each of the set sizes 2, 3, 5, and 8. Each item in each of the displays was probed as the target an equal number of times as illustrated by the gray dashed arrows. (See also Figure 1.) The bottom panel depicts the relevant set condition for each of the set sizes 2, 3, 5, and 8. In each set size eight items were always present in the search array. However, only a subset of the items were probed as indicated by the gray dashed arrows. Each item in the in the subset was probed as the target an equal number of times. The gray arrows are presented for illustrative purposes only; they were not present in the actual experiment. In addition, in both conditions set sizes were blocked.

participants were using memory to report the presence or absence of the target then not only should RTs to report the target have decreased across repetitions, but eventually search slopes should have approached zero because participants should have been able to locate the target directly using memory. Instead positive search slopes (approximately 35 ms/item) were obtained across as many as 350 repeated search trials.

Therefore, Wolfe and colleagues (2000) argued that observers rely on vision and search through the display when it is available; that is, they concluded that visual search tasks are memory-free. However, positive search slopes are only obtained if the visual display is present when participants are asked to make their response. If the visual display is removed during test and only the target probes are presented then participants' RTs are independent of the number of items in the display, showing that participants do, in fact, learn which items were present in the display (Oliva, Wolfe, & Arsenio, 2004, see Kunar, Flusberg & Wolfe, submitted, for an alternative response mapping explanation of these results). Therefore, Wolfe et al.'s results have an alternative interpretation that learning does occur in repeated search displays; in the very least participants learned what items made up the display. However, because search slopes remained positive, they interpreted their data as evidence that participants do not learn to associate the individual display items with their locations.

In contrast, Chun and Jiang (1998) demonstrated that subjects can learn the locations of items in repeated search displays. They showed participants a mixture of displays, some several times ("old" displays) and some only once ("new" displays, Figure 3). The locations of the items were invariant in "old" displays (item identity could vary). Participants' task was asked to report the facing direction of a T (oriented to the right or left). A target was present on every trial. Even in "old" displays participants had to orient

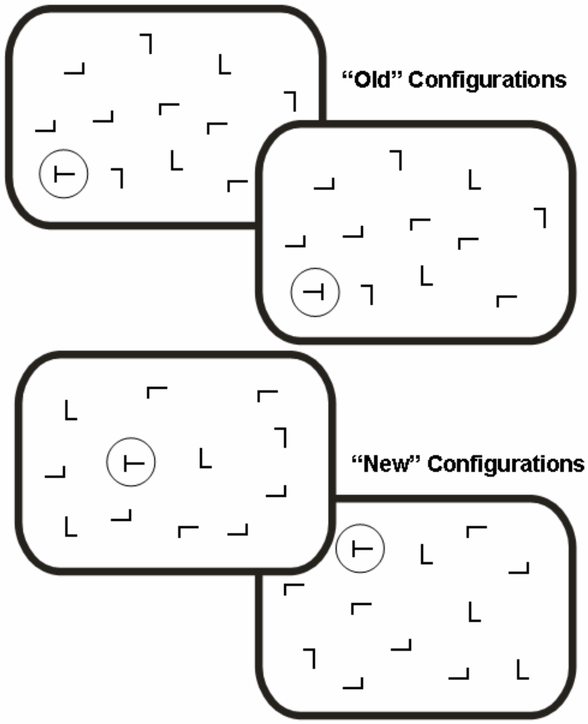

Figure 3. Example of displays used by Chun and Jiang (1998). Participants were asked to report the facing direction of a rotated target "T" among multiple distractor "Ls". The target is circled for illustrative purposes. The top pair of frames depicts an example of "old" displays. Note that while the facing direction of the target changes its location and the locations of the distractors are invariant. The bottom pair of frames depicts an example of "new" displays. Note that both the locations of the target and distractors changes across displays.

their attention to the target location because facing direction of the target varied. Chun and Jiang found that subjects moved their attention to target locations embedded in "old" configurations more quickly than in "new" ones. Because they used displays with a constant number of items (except their Experiment 4) they simply looked at the change in the amount of time to locate the target across blocks of trials rather than search slopes which rely on changes in display size. However, in Experiment 4 where set size (8, 10, or 12 items) was varied they found that their results were due to a reduction in search slopes and therefore, an increase in search efficiency rather than a simple reduction in intercept. Participants could not learn the pairings between item identity and location in this study because the identity of the items could change across repetitions of “old” displays – rather participants only learned the likely location of the target based on the configuration of the distractor locations.

Chun and Jiang (1999) extended this finding to learning the identities of items under conditions where the spatial layout of the display changed across trials, but the identities of the items making up the configuration were the same for “old” displays. Participants were asked to detect a target item that was symmetric around the vertical axis in a display made up of novel objects (see Figure 4). The target was always present, but accuracy of the response was analyzed by asking the participant to localize the target following each trial. This was accomplished by presenting numbers in place of the display items and asking participants to name the digit presented in the target location. They found that RTs to targets in “old” displays were faster than to targets in “new” displays, indicating that participants learned the association between the distractor identities and the target identities. Note, that as before participants could not learn the pairings between the item identity and its location because the locations of the items changed across repetitions of “old” displays – rather participants only learned which item was likely to be the target based on the configuration of distractor identities. Chun and

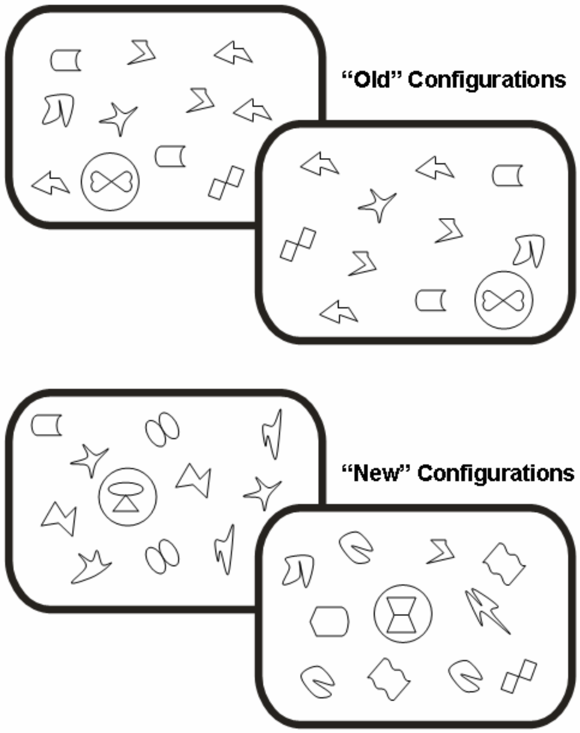

Figure 4. Example of displays used by Chun and Jiang (1999). Participants were asked to detect a target defined as symmetric around the vertical axis as quickly as possible. The target is circled for illustrative purposes. The top pair of frames depicts an example of "old" displays. Note that while the locations occupied by the items change across displays the identities of the items are invariant. The bottom pair of frames depicts an example of "new" displays. Note that both the identities and locations of both the target and the distractors change across displays.

Jiang termed the learning observed in both these studies "contextual cueing" because either the context of distractor items or the distractor locations served as a pointer to the target. These contextual cueing effects suggested that either location or identity memory can play a role in a visual search task. Furthermore, this learning was implicit and appeared rapidly, occurring after as few as four to five repetitions of each “old” display. It also had a high capacity, allowing at least 60 displays to be learned.

1.2 Learning of Location versus Identity Information

Past research has established that learning can take place in a search task (e.g. Chun & Jiang, 1998, 1999, 2003; Jiang & Chun, 2001; Olson & Chun, 2001, 2002). However, much of this work has focused on the extracting invariance across either the spatial configuration of the display or the identities of the items that have made up the display. Moreover, it has been shown that learning one type of information (location or identity) is robust to changes across the other dimension, such that learning can transfer. For instance, Chun and Jiang (1998) found spatial layout learning transfers across item changes such that when participants were trained to search for a 2 or 5 among square-shaped distractors their learning immediately transferred when the distractors changed to new shapes (rotated 2s and 5s) occupying the same locations. In addition, Nabeta, Ono, and Kawahara (2003) found that after participants were trained on a visual layout the learning transferred to a tactile search task.

However, it would also be a significant limitation on the visual system if the learning of both location and identity could not occur concurrently. In fact, learning the likely location of an item might be considered particularly important in a repeated search context, where identity-location pairings reliably co-occur and this knowledge could contribute to faster RTs than if only the identity or the location of the item were learned. Consistent with these ideas, Jiang and Song (2005) obtained evidence of spatial layout learning that was dependent on the color of the display items. As in Chun and Jiang's (1998) experiments participants were asked to report the facing direction of a target, "T" amongst rotated distractor "Ls". Half the displays presented were "old" in that their spatial layout was consistent across trials, while the other half were "new". During training participants were placed in one of three conditions: black items on all trials, white items on all trials, black items on half the trials and white items on half the trials. They found that if all the items were black during training there was transfer of learning for the spatial context at test when the items were white and vice versa. In contrast, if during training some trials contained black items while other trials contained white items, learning of the spatial context was contingent on the item color. That is, participants were not faster to report a target's presence in an "old" versus "new" configuration if during training the items were black and during test the items were white; they were only able to use the spatial context, resulting in faster RTs to "old" versus "new" displays if the color of the items in the display matched across training and test. However, this effect relied solely on intermixing black and white displays during training. From these results Jiang and Song concluded that spatial context learning can be identity contingent, however, while these results show that learning can be color contingent, a change of a simple feature, like color does not necessarily equate to an identity change (c.f. Huang, 2006).

However, Jiang and Song (2005) reported similar results in another experiment designed to alter the identity of the search items by making a small change to the shape of the "L" distractors. Two different sets of "L" distractors were created by changing the offset in the junction between the two line segments making up the letter. In one set the difference was small (0.1°), while in the other set it was larger (0.3°). This resulted in a subtle change in shape, although all the distractors could still be identified as “Ls”. As before the context effects were identity contingent when participants were exposed to both sets of distractors during training. If only one set was presented during training then learning transferred to the new set at test. However, as with a simple featural change to color it is unclear whether Jiang and Song have successfully changed the identity of the items in their displays; despite the varying the offset of the junction all the distractors could still be identified as “Ls”.

Jiang and Song (2005) claim their results show that context effects can be contingent on item identity when both location and identity are useful during training. That is, when the identity of an item can reduce the number of potential memory matches for a particular spatial configuration learning that configuration can become dependent on identity. For example, consider a case where participants needed to learn 24 displays and half of those displays were presented in a different color; if participants coded both the color and spatial layout of the items the number of potential matches for that display in memory is reduced from 24 to 12. In contrast, when the color of the items is constant across all training trials, spatial configuration is coded at a relatively crude global level, and learning of the layout transfers across changes to the item information. However, in both these experiments the changes to the distractor elements could be detected at a global level; there was no need to scrutinize the identity of individual items. For example, when the junction of the “L” distractors was made larger the “L” became more similar in shape to a “T”; therefore, participants may have simply monitored the display for distractors that were more or less “T-like” rather than attending to individual items. This calls into question whether or not these results truly demonstrate identity contingent learning, versus learning to monitor the displays for a change in the distractor color pattern or texture. Further, it is unclear to what degree individual items are being learned in a contextual cueing paradigm. That is, do participants learn to associate the identity of an item with the location that it occupies or is the coding cruder indicating only that a particular type of distractor maps onto a particular spatial layout, which in turn serves as a pointer to the target location?

Endo and Takeda (2004) further investigated the degree to which participants could learn both identity and location in a contextual cueing paradigm. In their experiments each display item had a unique identity given by a novel object. Participants were instructed to look for a target which was defined as the object with a closed contour (see Figure 5). As in Chun and Jiang’s (1999) study, a target was present on every trial and accuracy was assessed with a target localization task. An “old” display was defined by invariance across the spatial configuration (as in Figure 3), item identities (as in Figure 4), or both (combined condition; see Figure 5). As in previous studies context learning was measured as faster RTs to “old” compared to “new” displays. Endo and Takeda found that when both item identity and spatial configuration (combined condition) were invariant the effects were additive; that is RTs were faster than when either identity or spatial configuration alone was invariant. Their results, like Jiang and Song’s (2005), depended on training; all trial types had to be intermixed. When only “combined old” trials were intermixed with new displays during training participants

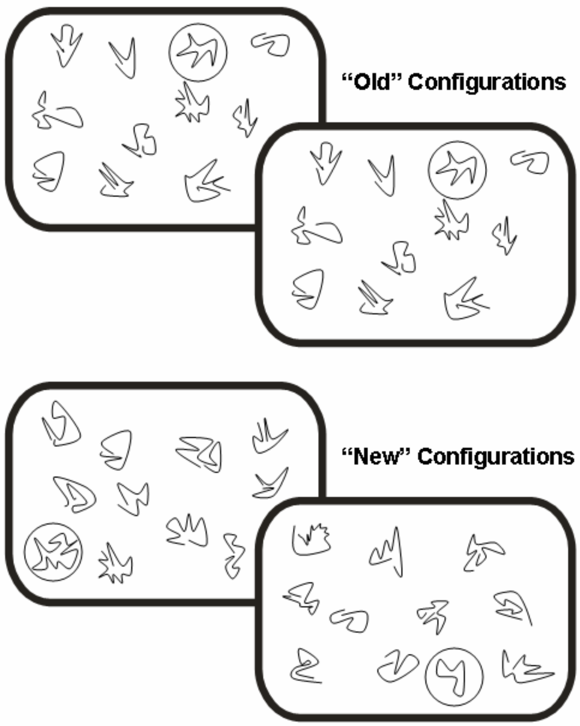

Figure 5. Example of the combined and new displays used by Endo and Takeda (2004). Participants were asked to detect a target defined as the enclosed object. The target is circled for illustrative purposes. The top pair of frames depicts an example of "old" displays. Note that the identities and locations of both the target and distractors remain invariant. The bottom pair of frames depicts an example of "new" displays. Note that the identities and locations of both the target and distractors change across displays.

relied on the spatial configuration alone at test as evidenced by no difference between RTs to "combined old" trials and "spatial old" trials; although RTs to these conditions were shorter than to "identity old" and "new" trials, which did not differ from each other. This is the first evidence which conclusively supports identity contingent learning of spatial configurations. Each object was a unique novel shape and therefore, changes in identity could not be monitored globally in terms of a change in texture or pattern.

Further, this study supports the idea that not all regularity and invariance in a display are necessarily used by the cognitive system. Endo and Takeda argued that this is because the learning mechanism must operate with a limited capacity and learning the “combined old” displays was computationally costly. Only under conditions, where both the identity and the location of the items was useful during training were the invariant contexts of both learned.

While the previous results show that under some conditions invariance in the display across both location and identity can be learned concurrently there is also some evidence suggesting that the location of an item affects visual search processes more than the identity of an item (e.g. Oh & Kim, 2004, Woodman & Luck, 2004; Woodman, Vogel & Luck, 2001). In fact, Lassaline and Logan (1993) have argued that an item’s location is more important to the attentional control system than its identity and therefore, is learned more readily. Many researchers have argued that one way memory might operate in a search task is by biasing attention away from previously examined locations (e.g. Klein & MacInnes, 1999; Muller & von Muhlenen, 2000; Takeda & Yagi, 2000). In fact, eye-movement data demonstrates that participants rarely re-examine previously fixated locations (e.g. McCarley, Wang, Kramer, Irwin & Peterson, 2003; Peterson, Kramer, Wang, Irwin & McCarley, 2001).

Beck, Peterson and Vomela (2006) recently investigated the role of location versus identity memory in the biasing of eye movements to new locations during visual search. Participants were asked to report the presence or absence of a rotated “T” target amongst rotated “L” distractors while their eye movements were recorded to examine their scan patterns during search. Each of these items was embedded in a larger outline colored (red, blue, yellow, or green) shape (circle, square, or triangle) in order to provide unique identity information to each item in the display. During the course of the search task sometimes the location or the identity (only the colored shape, not the letter located within the shape) of an item was changed during a saccade (the change occurred during a saccade to prevent participants from noticing a luminance change in the display). Beck et al. examined whether scan patterns were altered on these “change” trials compared to trials in which no change was made. They found an identity change did not seem to disrupt the search process, as participants were still able to bias fixations away from previously examined items regardless of whether the item had undergone such a change. However, when the location of an item changed it was re-examined more often than would be expected if the participants had memory for having inspected that item. Therefore, Beck et al. argue that participants have memory for the locations the items which they have examined, but not the identity of the items occupying those locations. However, they also report results from a pilot study that demonstrate when the target’s color and shape were held constant across all trials participants learned and used this information to increase search efficiency; both RTs and number of fixations needed to localize the target were reduced. (The color and shape of the target was not held constant in any of the other experiments reported by Beck et al.) Therefore, the results in this experiment differ depending on whether the item in question was a target or a distractor. If the target identity was held constant across trials it was learned and used to increase efficiency in target detection. In contrast, participants did not learn the identities of previously examined and rejected distractors, only their locations (for more on distractor memory see Beck, Peterson, Boot, Vomela & Kramer, 2006). One potential explanation for these results is that the design of this study biased participants to pay more attention to an item's location than its identity. Recall, that the target is a rotated “T”; therefore, encoding surrounding color-shape information was not necessary to perform the task because it was never part of a response decision. Consequently, participants did not learn the identity information.

The literature up to this point suggests that under some conditions learning the locations of the items in a display can be contingent on their identities (e.g. Endo & Takeda, 2004). It is important to note that in nearly all of the studies demonstrating memory in search reviewed here (with the exception of Beck et al., 2006) a contextual cueing paradigm was used. This is important because these studies cannot address whether observers can extract regularity regarding the likely locations of individual items, instead they demonstrate that participants can capitalize on the repeated context of distractor items in the “old” displays, which points them to the likely target. Further, it could be argued that learning both the location and identity of the items would be most valuable in optimizing target detection in a repeated search task like that used by Wolfe et al. (2000), where simply knowing which items make up the display or the which locations might contain targets alone is not enough. Every item and every location is potentially the target on each trial because, recall, Wolfe et al. probed all the items in the display an equal number of times.

1.3 More than a Context: Learning the Likely Location of a Particular Item

Two studies, one using a cueing paradigm (Kingstone & Klein, 1991) and the other using a search paradigm (Hoffman & Kunde, 1999) showed that learning can occur for the likely location of a particular item, but these studies have been neglected in the search literature. Kingstone and Klein asked participants to report the orientation of a letter (upright or inverted), under conditions in which each letter was more likely to appear in one location than in either of the other two locations. On each trial only one letter appeared. Before the task participants were given explicit instructions about which letter was likely (80% probability) to appear in a particular location. For example, a participant might have been informed that the "A" was likely in the 8 o'clock position while the "V" was likely in the 4 o'clock position. In addition, participants were provided with an arrow cue at the center of the display which indicated the likely location in which the letter would subsequently appear (80% probability). Participants were asked to try to use the information provided by the cue to prepare for the target stimulus. At the end of the instructions participants were quizzed in order to ensure they had learned the meaning behind the cues and the likely locations of the letters. They found that participants made faster orientation decisions when the target appeared in the cued location than the uncued location. Further, RTs were faster when the target was the likely letter versus the unlikely letter (c.f. Lambert & Hockey, 1986).

Hoffman & Kunde (1999) extended this work using a search paradigm. They examined whether participants could learn to expect a particular target in a particular location when participants were given neither attentional cues nor explicit information about target-location presentation frequencies (c.f. Miller, 1988). They presented participants with strings of letters which made up one of two global configurations: a wave or a bird shape. (These global configurations were used in order to examine a second question regarding whether relative position in a larger configuration could be learned.) Participants had to discriminate between one of two targets always presented in the displays. One target occurred in each of the display locations equally often (called the test target); while the other target (inducing target) appeared most often in a single location (critical location), regardless of global configuration. In addition, locations were coded as critical, adjacent (to critical) and remote (to critical). Hoffman and Kunde found that RTs were fastest to targets in the critical location than other locations, as was expected since regardless of identity targets appeared most often in that location. However, participants also learned to expect the inducing target at the critical location indicated by faster RTs to the inducing target than the test target at the critical location. In addition, participants learned to expect the test target at remote locations as indicated by faster RTs to the test target than the inducing target at the remote locations. However, RTs to each of the targets were similar in the adjacent conditions, indicating that participants did not have a consistent expectation that the test target was more likely than the inducing target to appear at these locations.

Hoffman and Kunde’s (1999) study provides evidence participants used location to help set expectancies about which target identity should occur in at least the critical and remote locations, given that RTs were faster to the inducing target than the test target in the critical condition, but the opposite response pattern was observed in the remote locations. However, it is unclear what participants learned at the adjacent locations. If participants had fully learned identity-location probabilities then RTs should have been faster to the test target than the inducing target at the adjacent locations, but no RT differences based on identity were observed at this location. Therefore, it appears that target expectancies were not assigned to specific locations. Instead there may have been a graded spread of target expectancy across location such that participants expected the inducing target at the critical location and as the distance from that location increased the expectancy of observing the inducing target in that location decreased and the expectancy of observing the test target in that location increased.

Given that the studies detailed above indicate that participants can learn to expect a target in a given location based on its identity why might researchers investigating the role of memory in a visual search task not have considered these studies relevant? First, Kingstone and Klein (1991) used a cueing paradigm and therefore, researchers investigating visual search may have considered their results to be, at best, tangentially related and, at worst, irrelevant. Therefore, over time this work may have been forgotten. It is also possible that researchers have discounted these results. As, pointed out previously it is unclear to what degree participants in Hoffman and Kunde’s (1999) study learned to associate a particular target to its likely location because of the ambiguous results obtained in the adjacent location condition. Further, much of the work reporting learning in a search task has relied on RT differences between a condition in which learning was expected compared to a condition in which no learning was expected (e.g. Chun & Jiang's (1998) comparison between "old" versus new" displays), whereas the literature claiming that there is no memory in a visual search task has more commonly relied on search slope data (changes in RTs across display size in a single condition). Recall, that all of the studies (except Chun & Jiang, 1998, Experiment 4) demonstrating learning in a search task presented the same number of items across all trials and therefore, could not examine search slopes. In contrast Wolfe and colleagues (2000) varied the number of items across blocks of trials which allowed them to use search slopes as their dependent measure to argue that search is memory-free. They reasoned that because search slopes remained positive over time participants had not learned the locations of the targets; if they had search slopes should have flattened and approached zero.

Despite the fact that some of the studies reviewed above have been given short shrift in the literature they provide strong evidence that participants can learn at least some components of a search display in both repeated and non-repeated search tasks. Participants are able to extract identity independent of location (e.g. Chun & Jiang, 1999), location independent of identity (e.g. Chun & Jiang, 1998), and spatial probability, indicating the likelihood a particular location will contain a target (e.g. Klein &

Kingstone, 1991; Hoffman & Kunde). Finally, depending on task constraints, there is some evidence location and identity can be learned concurrently (e.g. Endo & Takeda, 2004; Klein & Kingstone; Hoffman & Kunde, 1999). The current study seeks to, in part, further investigate the task constraints on learning the association between identity and location information. That is, do participants learn the likely location of a target under conditions where each location contains a target equally often and each target is probed equally often, but each target occurs more often in one location than the other? Under these conditions neither location nor identity alone will be sufficient for learning. For instance, in Hoffman & Kunde's study learning which location was most likely to contain the target may have been greater than learning what item would occur in that location because one location was probed more often than any other, whereas each target identity was probed equally often. This may have contributed to their ambiguous results. Further, while previous work has focused on examining identity and/or location memory, I argue that much more can be extracted in a repeated search display. I plan to investigate whether participants can learn two additional sources of display regularity. (1) The relative probability with which a particular target occurs in a particular location. Hoffman and Kunde's (1999) work points to the extraction of probability information, but participants seem to learn absolute probability rather than relative probability, given that RTs are always fastest to the location which was probed most often. (2) The direction from fixation to the target. It is often the case in a search task that each trial begins with the presentation of a fixation cross. Therefore, search begins from this location.

Participants may be extracting the regularity about the direction from fixation to the target and capitalizing upon this stability in order to better learn their display.

1.4 The Role of Competition in Producing Positive Search Slopes

Recall that Wolfe and colleagues (2000; Oliva et al., 2004) found that search slopes remained positive across hundreds of trials and from these results concluded that participants continue to search through repeated displays. However, Wolfe and colleagues (e.g. Oliva et al., 2004) also demonstrated that item information was learned under such conditions because after a training period when they removed the display and only a target probe appeared participants could report whether or not the item had been a part of the training display. Furthermore, RTs to make this decision were independent of the number of items that had been in the display, indicative of memory for the display. Positive search slopes were only evident in this task when the display was present. Are there other reasons why search slopes remain positive when the display is present? Suppose that as display is seen repeatedly information about the display is extracted and learned. Memory for the display may include the association between the item and location it occupies, the relative probability with which an item has been found in a particular location, the frequency with which an item has been probed, the direction to the target from fixation, to name a few. Each time a repeated display is seen these memories for the display are reactivated. Reactivated memories compete and the time it takes to accomplish target verification could vary depending on the relative activations of other display items. For instance, each entity in the display has some low level of activation due simply to its presence. Activation for a particular entity depends on factors such as the number of times it was probed as the target or the number of times it was presented one location versus another. Consequently, the total time needed to verify target presence relies on resolution of competition from among memories in the display. The greater the number of entities with similar activation levels, the stronger the competition among items and the longer it takes to verify target presence or absence. (See the General Discussion for further discussion of computational models which can implement this competition hypothesis.)

The above discussion makes clear that a number of factors beyond the number of display items and target/distractor similarity may affect RTs to targets. Under conditions like those in Wolfe and colleagues' (2000) experiments where multiple targets which always occupied the same location were probed equally often, no single memory for the target-location association was privileged. Rather, these memories competed with one another equally. Therefore, if RTs to verify target presence are determined by the amount of competition in the display which arises from both the number of memories regarding various learned components in the display and the strength of a given memory then it is possible that the time it takes to resolve the competition in the display produces positive search slopes, that Wolfe et al. took as evidence for memory-free search. As the number of items in their displays increased so did the competition and RTs to verify the target. Therefore, positive search slopes cannot be taken as evidence that participants rely on vision rather than memory in search.

1.5 Précis

The current study seeks to help resolve the polemical debate about the role of memory in a repeated visual search task by demonstrating that competition among memories for a display can produce positive search slopes when, in fact, participants are learning a great deal of information from repeated search displays. I will show that (1) RTs can be independent of the number of items in the display under conditions where only a subset of the items in the display are probed as targets (2) Participants are able to learn the association between a target and its location, the relative probability with which a target appears in a given location, and the direction from fixation where a target is located. Further, I will offer one potential mechanism by which this learning may occur.

In Experiment 1 I investigated the role of memory in a repeated search task using a design like that used by Wolfe et al. (2000), but added a condition in which eight items were always presented, but only a subset of those items were probed as targets. I found that it is the number of relevant items probed as the target that determined the search slope rather than the total number of display items indicating that participants do not search through all the items in the display. I argue that participants are learning the likely location of probed items in the display; that is the association between target identity and location. In Experiment 2, I ruled out an alternative explanation of Experiment 1 suggesting that participants did not learn the likely location of each target in the display, but rather learned to limit their search to a subset of relevant locations. In Experiment 3, I used a different paradigm to examine whether identity-location associations are learned across repeated displays. Two targets were only ever presented in two locations, but one target was more probable in location 1 than 2, whereas the other target was more probable in location 2 than 1. Despite the fact that each location was probed an equal number of times RTs were faster when a target was in its probable versus improbable location. Finally, in Experiment 4 I showed that participants learn the direction from fixation where they are likely to locate the target and propose that this direction information may serve as a mechanism by which learning of the display might be instantiated. These results demonstrate that participants have a great deal of memory for a repeated search display and can use this information to reduce RTs to report target presence or absence.

2. EXPERIMENT 1

Experiment 1 was designed to obtain evidence that it is the number of probed items in a display rather than the number of display items that dictates RTs in a repeated visual search task. There were two conditions: (1) A "display set" condition: like Wolfe et al. (2000) participants viewed repeated search displays containing 2, 3, 5, or 8 items multiple times (each set size was blocked), see Figures 1 and 2. In each block every display item was probed as a target an equal number of times. I expected to replicate Wolfe et al.'s findings. That is, as the number of display items increased so would RTs, producing a positive search slope. (2) A "relevant set" condition: the number of display items was held constant at eight, while the number of elements probed as the target varied (2, 3, or 5), see Figure 2. (Relevant set size was blocked.) This was the critical condition: If participants did not learn the locations of the probed items, but rather continued to perform visual search through the entire display then RTs in each relevant set condition should look similar to RTs in the display set size eight condition. This is because regardless of the number of items probed there were always eight items in the display. That is, search slopes in the relevant set condition should be flat if no learning occurred. Note, that flat slopes in the relevant set condition would not be indicative efficient search, but rather that participants searched through all eight items on every trial regardless of relevant set size. However, if subjects learned the locations of the probed items then RTs should be shorter when two items were probed than when three items were probed and so on, and search slopes in the relevant set condition should be similar to search slopes in the display set condition.

2.1 Method

2.1.1 Participants

Twelve participants (7 F) were recruited from the University of Arizona. Participants were naïve volunteers who were either members of the Visual Perception Lab or paid $10 for their participation. All subjects had normal or corrected-to-normal visual acuity. All participants' error rates were less than or equal to 15% per condition and 10% overall, which was the criterion set for exclusion of a participants' data from further analysis. This exclusion criterion applies to all the subsequent experiments in this study.

2.1.2 Stimuli and Apparatus

The display elements were presented in black uppercase Verdana boldface font at 38 point on the invisible circle. Target probes were presented at fixation in black lowercase Verdana boldface font at 30 point. Wolfe et al. (2000) used this technique of mismatching the target probe and display items' case in order to help differentiate the probe from the search set in their experiments, although similar results have been obtained even when the target probe and display items' makeup were identical (Wolfe, 2003). The display letters were chosen randomly without replacement from 16 of the letters making up the Roman alphabet (A, B, C, E F, H, I, J, K, M, P, R, Q, S, T, U). Sixteen letters were used rather than the entire Roman-letter alphabet because only 16 objects were ever used by Oliva et al. (2004) and I wanted to emulate their design for this initial replication. Display letters were placed in some or all of eight equally spaced locations on an invisible circle whose diameter subtended 8.3° visual angle. This ensured that each of the display elements was the same distance from the target probe item which was placed in the center of the imaginary circle (see Figures 1 & 2).

In the display set condition, each display was created by randomly sampling 2, 3, 5, or 8 items without replacement and placing each item in one of the eight possible positions on the imaginary circle. The items and their locations remained constant throughout the entire block. Four different programs were created, each using a unique display, for each set size (totaling 16 unique displays). Programs were counterbalanced across participants. For each target present trial one of the items presented in the display was chosen and presented at the center of the invisible circle. For each target absent trial one of the items not presented in the display was chosen from amongst the items remaining in the set of possible letters (16 - display size). Likewise, in the relevant set condition, a display was created by randomly sampling eight items without replacement and placing each item in one of the eight locations on the imaginary circle. As in the display set condition, the items and their locations remained constant throughout the entire block and four different programs were created, each using a unique display, for each relevant set size (totaling 12 additional unique displays). For each target present trial an item was chosen from among a subset of the items presented in the display (2, 3, or 5 depending on the set size block). (No relevant set size eight was included because trials in that condition would have been equivalent to the display set size eight condition.) For each target absent trial one of the 8 items not presented in the display was sampled from amongst the remaining items in the set of possible letters.

The experiment was run on a personal computer Gateway E-6300. The search display was presented on a 21-inch Sony monitor. Subjects viewed the monitor from a distance of 96 cm, with their head position maintained by a chin rest. A custom-built button box with two horizontally arranged buttons was used to record subject's present/absent responses. Subjects used a foot pedal to advance through the instructions and recommence the experiment following breaks. The presentation and response measurement software was DMDX (Forster & Forster, 2003).

2.1.3 Procedure and Design

Instructions were presented on the computer screen prior to each block; subjects read them at their own pace. Following each set of instructions there were 16 practice trials to allow participants to familiarize themselves with the task and the equipment used to make their responses. Trials proceeded as follows: On the first trial a fixation cross appeared for 500 ms. Following the presentation of the fixation cross the search display and the target probe were presented simultaneously. The target probe remained visible until response or 3 seconds elapsed, whichever came sooner. The display, however, was presented continuously until a break. After half the trials in each block participants were given a break. Breaks had a mandatory 5 second rest period with the option of resting longer. Following the break the trials recommenced as described above and the display continued to remain visible from trial to trial until the completion of a block. Therefore, for the majority of the trials the display was continuously visible and the only change on the monitor was the presentation and removal of the fixation cross and probe item. Each trial sequence followed the one before automatically.

Each participant performed seven blocks of trials each containing 160 trials for a total of 1160 trials. There was one block of each of the following conditions: display set sizes 2, 3, 5, and 8 and relevant set sizes 2, 3, and 5. Block order was counterbalanced such that half the participants performed the display set size condition prior to the relevant set size condition and the remaining half did the opposite order. Set size was counterbalanced within each condition.

For each block half the trials (N = 80) were target present trials. On these trials, each target was probed equally often. For example, in the set size two blocks each of the two targets were probed 40 times; in the set size three blocks, two of the targets were probed 27 times each while the third target was probed 26 times. For target absent trials (N = 80) a new probe was chosen for each trial from amongst the letters remaining after display items were removed from the set of 16 possible items. For example, when there were eight items in the display target absent probes were chosen randomly from amongst the eight remaining letter choices, whereas when there were five items in the display, target absent probes were chosen from amongst the 11 remaining letter choices and so on. Both target present and target absent trials were presented randomly within each block. The experiment lasted approximately two hours.

2.2 Results

Mean correct RTs were calculated for each set size condition. RTs that were more than two standard deviations from the individual's condition mean were excluded. This resulted in the elimination of 4.5% of the data. Trials on which errors were made were eliminated before the RT data were analyzed.

Participants showed evidence of having learned the locations of the probed items in the relevant search set. Set size effects were the same across the relevant set and display set conditions despite the fact that there were always eight items present in the display in the relevant set condition, indicating that search slopes were equivalent in the two conditions (see Figure 6A & B). A repeated measures ANOVA with the factors condition (display set and relevant set), set size (2, 3, and 5) and target type (present and absent) was performed on the data. (Set size eight was not included in this ANOVA because it was only run as a part of the display set size condition.) The ANOVA revealed a main effect of set size (corrected by Greenhouse-Geisser for a violation of the assumption of sphericity[1]) indicating that as either the number of items in the display increased or the number of relevant items probed as targets in the display increased, RTs increased, $F(1.3, 13.9) = 50.1$, $p < .001$. In addition, a main effect of target type revealed that RTs were faster on target present (528.9 ms) trials than on target absent trials (602.3), $F(1, 11) = 34.3$, $p < .001$, as is typical in a search task.

[1] A violation of sphericity refers to unequal variances between the differences across conditions. The Greenhouse-Geisser correction adjusts the degrees of freedom used to evaluate the F-ratio. It is considered the most conservative correction for sphericity violation (Greenhouse & Geisser, 1959).

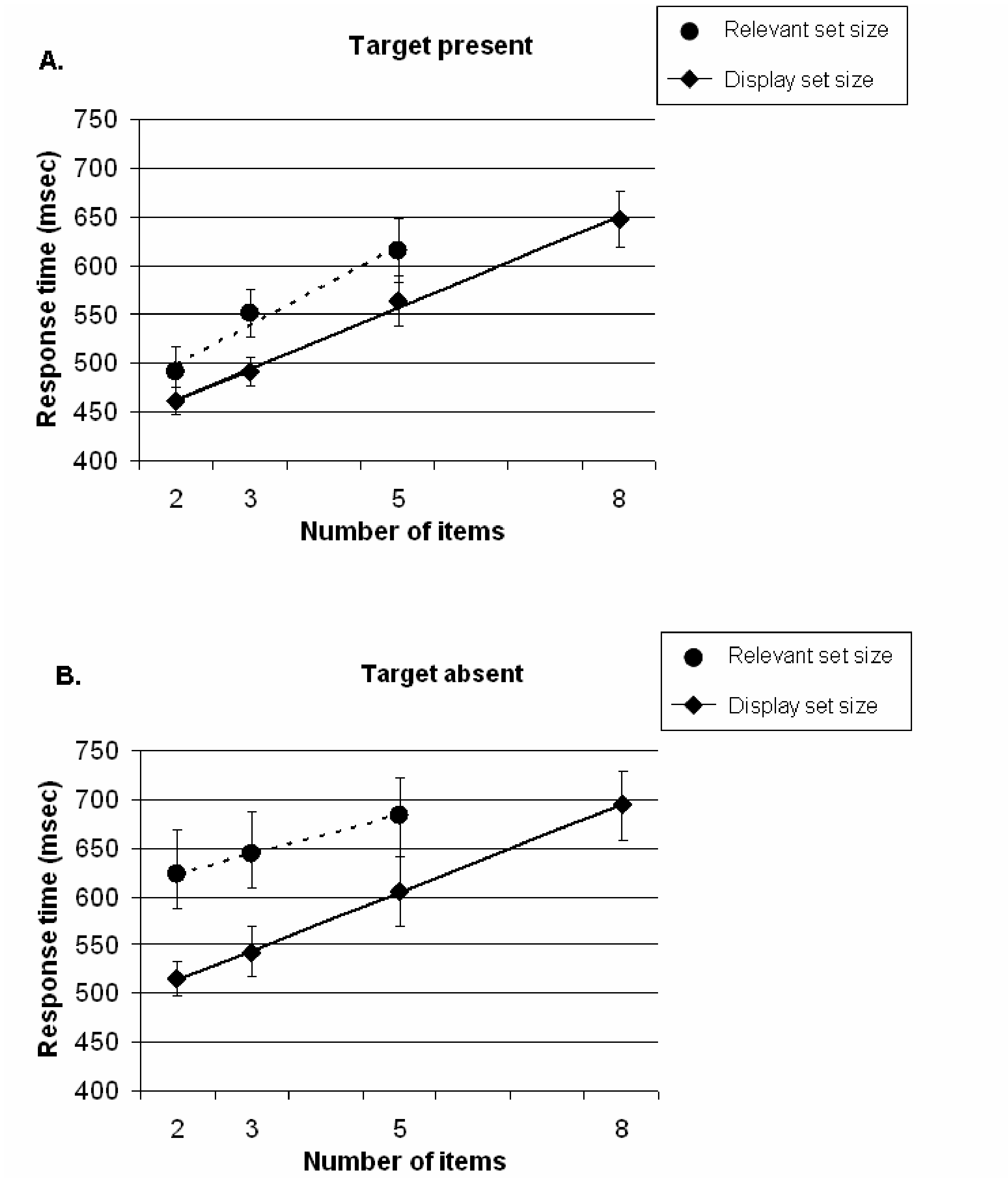

Figure 6. Experiment 1 mean RTs graphed as a function of set size for: A. target present trials and B. target absent trials. Display set size depicted with a solid line. Relevant set size depicted with a dashed line.

The ANOVA failed to show an interaction between condition and set size, $F(2, 22) = .1$, $p > .9$, indicating equivalent search slopes across conditions. This provides evidence that participants were not searching through all eight items in the relevant set condition, but instead learned the likely locations of the targets. There was a marginal three-way interaction between condition, set size, and target, $F(2, 22) = 2.8$, $p = .08$. The marginal three-way interaction was the result of steeper search slopes for target present than target absent trials in the relevant set condition, but not in the display set condition (see Figures 6A & B). Separate ANOVAs performed on the relevant set and display set conditions with the factors set size (2, 3, and 5) and target type (present and absent) revealed an interaction between set size and target type in the relevant set condition only, $F(2, 22) = 7.2$, $p < .005$. For target absent trials participants typically increase their response criterion in order to be certain that a target is not present; this leads to longer RTs to target absent trials than target present trials. The presence of additional items in the relevant set condition compared to the display condition increases noise in the display. This increased noise may add to RT increases due to raised criterion because the noise in distractor locations may exceed threshold on some trials and those locations may have been checked before an absent response was created. (This checking process does not necessary imply a serial search of these additional locations; see the discussion following Experiment 1 for more on this topic.) Further, one might expect that the greater the number of additional unlearned locations in the relevant set condition the greater the likelihood that one or more of these locations would exceed threshold and attract attention. For example, in the relevant set size two condition there were six additional locations which contained items, whereas in the relevant set size five condition there were only three additional locations which contained items. It is more likely that a greater number of distractor locations would exceed threshold in the case of the relevant set size two condition than the relevant set size five condition. This means that search slopes would be shallower for target absent trials than for target present trials where no additional locations would need to be examined. In the display set condition there were no additional distractor locations which could attract attention and therefore, no interaction was observed between target type and set size. Finally, in order to further evaluate this three-way interaction to ensure that it was not an indication that participants were not learning in the relevant set condition, but rather searching through all eight items, I also performed separate analyses on target present compared to target absent trials to look for a condition by set size interaction. Each of these ANOVAs failed to show an interaction between condition and set size, $Fs < .6$, $ps > .5$.

The three-way interaction subsumed interactions between set size and target type, $F(2,22) = 8.6$, $p < .005$, and between condition and target type, $F(1,11) = 6.8$, $p < .05$. Search slopes were shallower on target absent trials than on target present trials. This interaction was driven primarily by the relevant set size condition, see the explanation above. Finally, there was a main effect of condition, $F(1, 11) = 7.5$, $p < .05$, which was modified by the interaction between condition and target type, indicating that RTs were faster in the display set condition (529.7 ms) compared to the relevant set condition (601.5 ms). Despite the fact that participants did not search through all eight items in the relevant set condition, the mere presence of those additional display items in the relevant set condition compared to the display set condition may have produced greater noise in the display which increased overall RTs. Further, because participants increase their response criterion on target absent trials the presence of this noise was more likely to affect target absent than target present trials.

Search slopes in the relevant set condition were analyzed independently of the display set condition because if search were memory-free in the relevant set condition one would expect flat search slopes in that condition. The mean search slope across subjects in the relevant set condition was 30.1 ms, which is significantly greater than zero $t(11) = 3.4$, $p < .01$, two-tailed. A t-test examining search slopes across target type (present or absent) revealed that the search slope was steeper for target present (40.1 ms) than for target absent (20.2 ms) trials. This was likely due to the fact that participants checked more locations before making a response on target absent compared to target present trials (see above discussion). In addition, for target present trials, RTs in the relevant set size two and three conditions were significantly shorter than in the display set size eight condition (8: 647 ms, 2: 491 ms, $t(11) = 8.2$, $p < .001$, two-tailed; and 3: 551 ms, $t(11) = 3.1$, $p = .01$, two-tailed). RTs in the set size five condition were shorter, although not significantly so (615, $t(11) = 1.1$, $p > .3$). This provides additional evidence that participants were not searching through all eight items in the relevant set condition; had they done so RTs in all the relevant set size conditions should have been equivalent to the display set size eight condition. Likewise, in the display set condition the search slope was 32.3 ms, which is significantly greater than zero, $t(11) = 4.3$, $p < .005$, two-tailed. In the display set condition search slopes did not differ across target type (present and absent).

Error rates were low (2.4%). An ANOVA with the factors condition (relevant set and display set), set size (2, 3, and 5) and target type (present and absent) was performed on the error data. Participants were more likely to make errors on target present (3.5%) compared to target absent trials (1.5%), indicating a bias to say "absent", $F(1, 11) = 16.3$, $p < .005$. In addition, there was an interaction between condition (relevant set size and display set size) and target type (present and absent) indicating that participants made more errors on target present trials in the relevant set size condition (3.9%) compared to the display set size condition (3.1%), but fewer errors on the target absent trials in the relevant set size condition (1.3%) compared to the display set size condition (1.8%). As with the RT data, this greater bias to say "absent" in the relevant set condition compared to the display set condition is likely due to noise from the additional items present in the search display in the relevant set condition. There was no evidence of a speed-accuracy tradeoff in these effects.

2.3 Discussion

Experiment 1 demonstrates that search is not memory-free. RTs obtained in the relevant set condition are inconsistent with the hypothesis that participants were searching through all eight items in the display. In fact, search slopes in the relevant set condition were equivalent to search slopes in the display set condition. On a memory-free search hypothesis if participants were searching through all eight items in the display in the relevant set condition regardless of the number of items probed, search slopes should have been equivalent to zero; this was shown not to be the case. Further, despite the fact that participants showed learning in the relevant set condition RTs still increased as the number of relevant target items increased. This is consistent with the hypothesis that competition between equally probed locations produced positive search slopes; as the number of probed items which were eligible for entry into the competition increased so did RTs. This finding demonstrates that positive search slopes cannot be taken as definitive evidence for memory-free search.

Further, these results are consistent with a hypothesis that participants have learned the association between each item and its location in a repeated search display. That is, participants have learned not only the items in the display as was previously demonstrated by Oliva et al. (2004), but also the location in which each item was likely to appear. However, the results of Experiment 1 are also consistent with an alternative "relative location search set" hypothesis; that participants were simply learning to search through a subset of the display. That is, in the relevant set condition participants have learned only which locations are likely to contain a target and, so, they searched only that subset of locations in the display to verify target presence. By this explanation participants did not know which location was likely to contain which target.

Palmer (1994, 1995) showed that participants can learn to search a relevant subset of locations that is smaller in number than the actual display size. Palmer's study differed from Experiment 1 in that he presented participants with cues indicating the relevant target locations and displays were never repeated. The cueing display was made up of black and white crosses; black crosses indicated the relevant locations where a target might be presented, whereas the white crosses indicated irrelevant locations where a target would never be presented. Participants were asked to report whether a target, defined as a disc that was higher in contrast than surrounding distractors, was present or absent. He found that RTs were faster to report target presence when participants were cued with a relevant set display than on displays containing the same number of items, but no cues. Despite this alternative, Experiment 1 demonstrates that learning can occur without the use of cues. Identifying a relevant set requires a substantial number of trials and, therefore, memory for the potential target locations. However, the data cannot conclusively distinguish between what type of memory is being utilized: only memory for the potential target locations (relevant subset) or competitive memory for the likely location of a target.

Finally, in Experiment 1 I argued that one reason search slopes were shallower on target absent trials than on target present trials in the relevant set condition was because more items were present in that condition than were probed, which increased noise in the display. This increased noise in distractor locations may have exceeded threshold on some trials and resulted in participants checking those locations. By checking I do not mean to imply a serial search process. The verb checking will be used throughout this paper because it does not imply the mechanism by which locations are further examined. Location checking could be instantiated in different ways. One possibility is that when a particular location is given greater attentional weight or exceeds threshold an attentional movement is made to that location. Another possibility is that differential attentional weighting results in higher resolution or lower thresholds at locations with greater weights. The data presented in Experiment 1 and in all other experiments presented herein do not allow me to distinguish between these possibilities and therefore, no assertions will be made about the mechanism involved.

3. EXPERIMENT 2

Learning in the real world often involves extracting statistical regularities from our visual environments. Consider the following example, in my kitchen the knife rack is located to the left of the kitchen sink with 100% predictability, but the toaster is typically found in one of two locations: on the counter next to the stovetop or in the bottom cupboard next to the sink. When looking for a knife from the example given above one should learn to always check to the left of the kitchen sink never the bottom cupboard. One of the goals of Experiment 2 was to examine whether participants were able to extract this type of regularity and learn the association between the identity information and the likely location in which to find that item.

Experiment 2 was designed to adjudicate between the relevant location search set (e.g. Palmer, 1994, 1995) versus the item-location association learning hypothesis laid out in Experiment 1 by comparing a two-relevant location condition to a three-relevant location condition. In the two-relevant location condition ten display items were always present, but participants were only ever queried about two of the items in the display. When present, each item always occupied the same location throughout the experiment; when absent a new letter was placed in its location (see Figure 7A). In the three-relevant location condition participants were also only queried about two items in the display; when present one of those items always occupied the same location (see Figure 7C), however, the other item was equally likely to occur in each of two locations (see Figure 7D). Targets that always occurred in the same location when present will be called

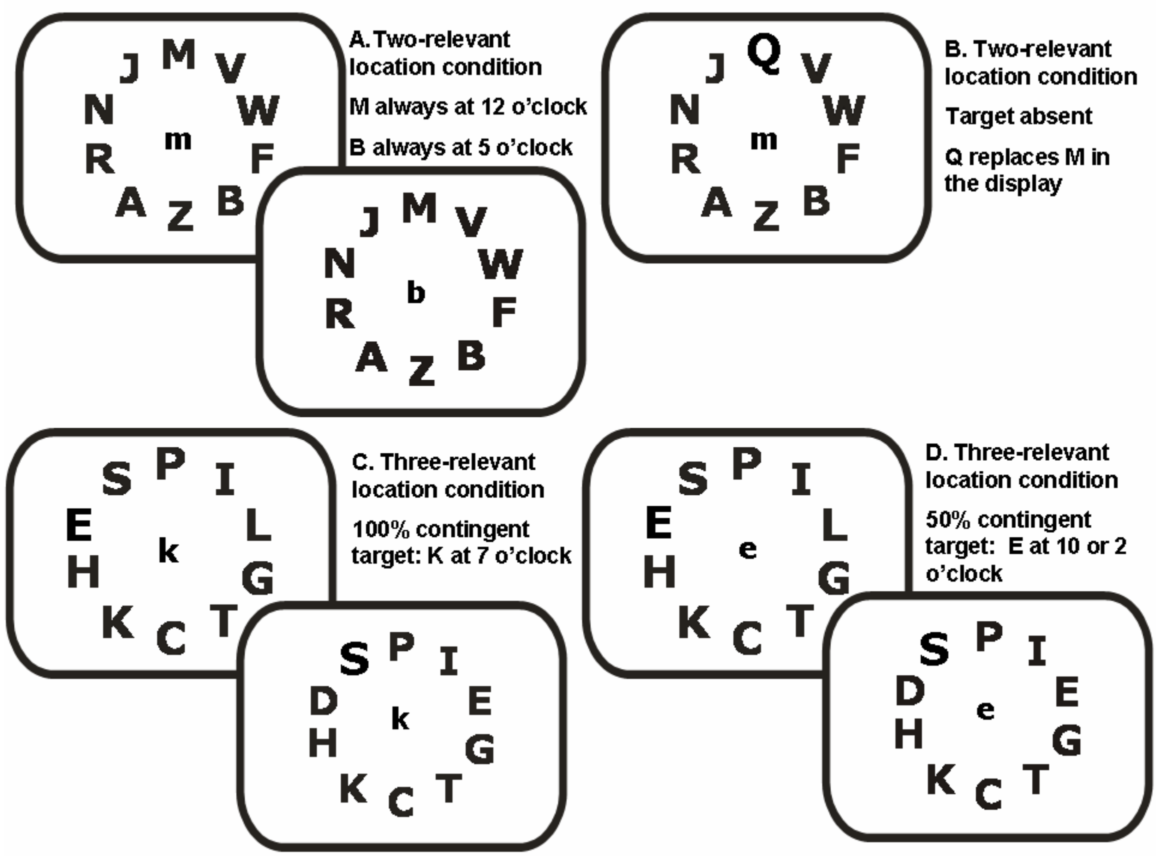

Figure 7. Depiction of the two-relevant location condition compared to the three-relevant location condition. Top panel depicts the two-relevant location condition. A. Target present trial, the "M" is always located at 12 o'clock and the "B" is always located at 5 o'clock. B. Target absent trial. "M" is paired with the target absent foil, "Q". When "M" is absent a "Q" replaces it in the display. The bottom panel depicts the three-relevant location condition for targets K and E. Target present trials only. C. Depicts the 100% predictable target "K", which is always located at 7 o'clock regardless of whether "E" is located at 10 or 2 o'clock. D. Depicts the 50% predictable target "E", which is either located at 10 or 2 o'clock.

"100% location predictable" targets and targets that occurred in one of two locations when present will be called "50% location predictable" targets.

To test the alternative relative location search set hypothesis from Experiment 1, I compared RTs to verify the presence of the 100% location predictable target item in the two- versus the three-relevant location conditions. If the results in Experiment 1 were due to participants learning to search a relevant location set then RTs to 100% location predictable targets should be shorter in the two-relevant location condition than in the three-relevant location condition. This is because under the relevant search set hypothesis participants are not be learning the likely location of a given item, but only the likely locations in which any target might appear. In the two-relevant location condition there are two such locations, whereas in the three-relevant location condition there are three. However, if participants were learning the likely locations of target items then learning should be approximately equivalent for items always shown in one location regardless of the probability with which another item might occur in a particular location and RTs to each of the two targets in the two-relevant location condition should be similar to RTs to the 100% location predictable target in the three-relevant location condition. In addition, RTs in the three-relevant location condition should be shorter to the 100% location predictable target than to the 50% location predictable target. This is because on some number of the trials when the 50% location predictable target is probed more than one location will have to be checked.

3.1 Method

3.1.1 Participants

Sixty-two participants (45 F) were recruited from the University of Arizona and received course credit for their participation. Thirty-one participants (22 F) were assigned to the two-relevant location condition and the remaining 31 participants (22 F) were assigned to the three-relevant location condition. All subjects had normal or corrected-to-normal visual acuity. Two additional participants (1F) were not included in the analyses of RT data because of high error rates.

3.1.2 Stimuli and Apparatus

The display letters were presented in black uppercase Verdana boldface font at 38 point. Target probes were presented in black lowercase Verdana boldface font at 28 points. For the two-relevant location condition, each target present display was created by placing ten randomly chosen letters from the Roman alphabet in equally spaced locations on an invisible circle whose diameter subtended 10° visual angle. Two probe items were selected from amongst the ten display items with the rule that there were at least three intervening locations between the two target locations (see Figure 7A). This was done in order to maximize the distance between the two target items to reduce the likelihood that participants would adopt a strategy of spreading their attention across the target locations. These two items served as the target probes for the entire session for an individual subject.

For the three-relevant location condition two different target present displays were created because the 50% location predictable target occupied one of two locations. The first display was created in the same fashion as used for the two-relevant location condition (see Figure 7C). The second display created by randomly selecting one of the target items and placing it in a new location. The original item occupying the target's second location was eliminated and a new item was placed in the target item's initial location (see Figure 7D). For the three-relevant location condition there were always at least three intervening locations between the two locations that a single target could occupy. In addition, the location of the 100% location predictable target was always at least one intervening location away from either of the two locations that the 50% location predictable target could occupy.

Target absent displays were created from the target present displays such that one of the target items was replaced with one of two randomly chosen new foil items, which had not previously appeared in the target present display. This pairing between the target present item and the target absent foil was consistent for all target absent trials. For instance, if “M” occurred 100% of the time at the 12 o’clock location for target present trials, when “M” was absent a “Q” always replaced the “M” in the display (see Figure 7B).

For each condition four different programs were created, each using unique displays. The order in which these programs were run was counterbalanced across participants. For the two-relevant location condition only three displays were ever presented to the subject: a target present display and two target absent displays (one display for each target absent foil). In contrast, for the three-relevant location condition six displays were presented to the participants: two target present displays and four target absent displays (two displays for each of the 100% location predictable foils, so that each 50% location predictable target position was represented and two additional displays for the 50% target location foil positions). All other elements of the stimuli and apparatus were identical to that used in Experiment 1.

3.1.3 Procedure and Design

Trials proceeded as follows: a fixation cross appeared for 500 ms. Following the presentation of the fixation cross the search display and the target probe were presented simultaneously. The display remained visible until response or 3 seconds elapsed, whichever came sooner. The next trial sequence followed automatically. Because of the change of design in this experiment there were multiple displays and therefore, no single display remained visible throughout the experiment. This differs from Wolfe et al. (2000) where the search display was presented continuously, but is still a form of repeated search because either eight elements in the two-relevant location condition or seven elements in the three-relevant location condition remained the same across all trials. In addition, each individual display was seen multiple times.

Each participant performed 2 blocks of trials each containing 64 trials for a total of 128 trials. After half the trials participants were given a 5 sec break with the option of resting longer. Each probe item was presented equally often. Half the trials were target present and half the trials were target absent. For the target absent trials the two original items served as target probes, but the target items' foil replaced it in the display. The other potential target item remained present in the display. For the three-relevant location condition each of the two target present displays was presented equally often for each target item to ensure that even when the 100% location predictable target was probed it was seen in the context of the other target being presented in each of the two locations it could occupy. Similarly, for the target absent trials when the 100% location predictable target was probed (and its foil replaced it in the display) the 50% location predictable target was shown in each of its possible locations equally often. Trials were presented randomly within each block. The experiment lasted approximately 30 min.

3.2 Results

Mean correct RTs were calculated for each condition and target location. RTs that were less than 150 ms or greater than 2000 ms were excluded. This resulted in the elimination of 2.5% of the data.

A mixed measures ANOVA with the within subjects factor target type (present or absent) and the between subject factor condition (two-relevant location or three-relevant location) for the 100% predictable targets revealed that RTs did not differ across conditions as might be expected if participants were learning the likely locations of the targets rather than searching through a relevant set of locations, $F(1, 60) = 1.1$, $p = .29$ (see Figure 8A & Table 1).[2] RTs were faster to target present trials than target absent trials as expected in a visual search task and indicated by a main effect of target type, $F(1, 60) = 349.6$, $p < .001$. Finally, there was an interaction between target type and condition

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[2] There were twice as many 100% location predictable trials in the two-relevant location condition than in the three-relevant location because both targets in the two-relevant location condition were 100% location predictable. I did not worry that this affected the analyses because not only were RTs to each of the two locations in the two-relevant location condition equivalent [$t(30) = 1.2$, $p > .24$, two-tailed], but the standard error rates for each location were similar to the standard error rate obtained when I averaged across these two locations. In addition, I performed t-tests to evaluate the differences to the 100% location predictable target across the two-relevant set size and three-relevant set size conditions and replicated the analyses done with the ANOVA. No differences were obtained when each location in the two-relevant set condition was compared to the three-relevant location condition separately, $ts < 1.3$, $ps > .20$, two-tailed.

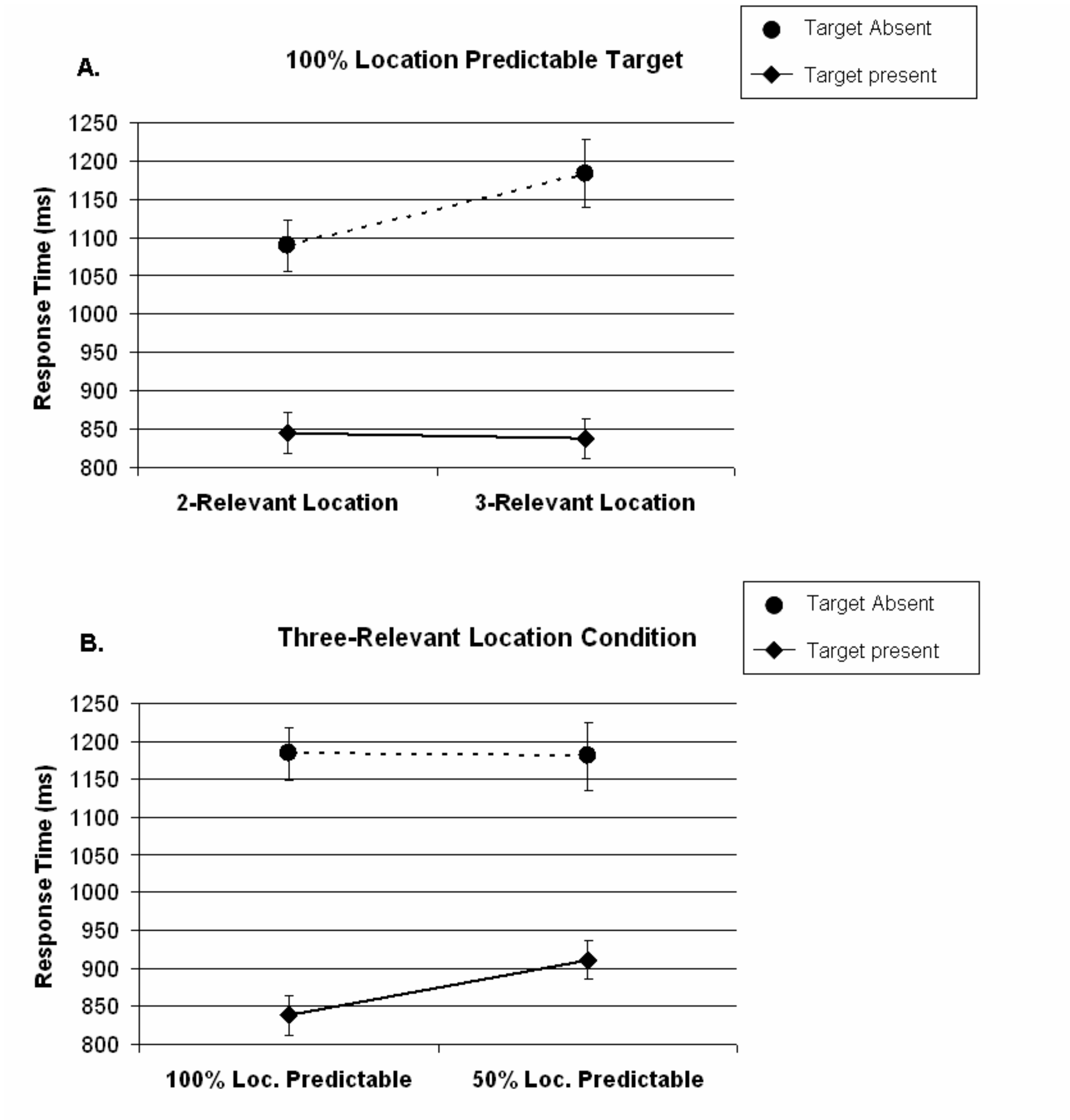

Figure 8. A. Experiment 2 mean RTs for the 100% location predictable target across the two-relevant and three-relevant set conditions. B. Experiment 2 mean RTs to the three-relevant location condition across the 100% location predictable and 50% location predictable targets. Target present trials depicted with a solid line. Target absent trials depicted with a dashed line.

Table 1. Experiment 2. Two-relevant location condition and three-relevant location condition mean RTs across target contingency (100% and 50% predictable) by location for target present and target absent trials.

Experiment 2	100 % Predictable				50 % Predictable			
	location 1		location 2		location 1		location 2	
	present	absent	present	absent	present	absent	present	absent
2-Relevant Loc	833.1	1076.9	856.7	1102.1	---	---	---	---
	(29.3)	(37.8)	(27.0)	(34.1)	---	---	---	---
3-Relevant Loc	838.1	1184.1	---	---	933.0	1188.8	889.5	1171.8
	(25.9)	(44.4)	---	---	(29.0)	41.6	(27.0)	(42.2)

Notes: Standard errors are in parentheses. Loc = Location showing that RTs to target absent trials were longer in the three-relevant location condition than in the two-relevant location condition, but there were no differences between conditions in the target present trials, $F(1, 60) = 11.2$, $p = .001$. This provides additional evidence that participants learned the likely locations of the targets. For target present trials RTs to targets in the 100% predictable location were no different from one another because participants had learned the likely location of that target and could check that location relatively quickly. In contrast for target absent trials participants appear to be checking all of the locations in which a target item had previously been located; that is three locations in the three-relevant location condition and two locations in the two-relevant location condition. As in Experiment 1 participants may also check some additional distractor locations because noise at those locations exceeded threshold. However, it is clear that participants are not checking all the display locations because this was held constant across the two-relevant and three-relevant location conditions, only the number of locations in which a target could appear varied. If participants had checked all the display locations no differences would have been obtained across conditions. Therefore, the time spent checking potential target locations was greater than time spent checking any distractor locations.

A within subjects ANOVA was conducted on the three-relevant location condition with the factors target contingency (100% and 50% location predictable targets) and target type (present and absent) in order to further examine whether participants were learning the likely locations of the target items. If participants were learning the locations of targets then RTs would be shorter for the 100% location predictable target because there is only one potential learned location associated with that item than the 50% location predictable target where there are two potential learned locations associated with that item and on some number of the trials participants would have to check more than one location. Indeed, RTs were longer to the 50% location predictable target than the 100% location predictable target, $F(1, 30) = 3.3$, $p = .08$ (see Figure 8B & Table 1). In addition, there was a main effect of target type; RTs were faster to target present than target absent trials, $F(1, 30) = 176.2$, $p < .001$. An interaction between target contingency and target type revealed that there was a greater increase in RTs to the 50% predictable target than the 100% predictable target for target present trials than for target absent trials, $F(1, 30) = 16.3$, $p < .001$. A t-test comparing target present trials across target contingency showed RTs were significantly longer to the 50% predictable location target than to the 100% predictable location target, $t(30) = 3.4$, $p < .005$. This is strong evidence showing that participants do not search through three relevant locations in this condition, because if they did RTs should be equivalent across target contingency; instead participants checked the likely location of the target (at least for the 100% location predictable target, it is possible that participants checked all three locations for the 50% location predictable target, see discussion, section 3.3 for more on this possibility). RTs to targets absent items did not differ based on target contingency, RTs to the 100% location predictable target were equivalent to RTs to the 50% location predictable target, $t(30) < 1$. This indicates that while participants learned the likely location of the target on target present trials, on target absent trials participants checked at least all the potential target locations (and possibly some of the distractor locations) in order to be certain that no target was present. Therefore, the target absent foil was not learned.

Finally, an ANOVA examining RTs to each of the locations in which the 50% location predictable target could occur revealed that RTs were faster to one location than the other, $F(1,30) = 4.3$, $p < .05$. This indicates that participants used a strategy of checking locations in a systematic order when verifying whether the 50% predictable target was present. It is unclear what strategy participants may have used. I can rule out the possibility that participants always checked from left to right or right to left because half the targets occurred on the left while the remaining half occurred on the right and the location coding of the programs was counterbalanced. However, it is possible that participants adopted a strategy of scanning from top to bottom because in all programs the location to which participants responded more quickly was always located at least one item above (though it may have been in the opposite left-right visual field) the location to which participants responded more slowly.

Error rates were low (4.2%). A mixed measures ANOVA with the within subject condition target type (present and absent) and the between subjects factor condition (two-relevant location and three-relevant location) for the 100% predictable targets revealed only a difference in error rates on target absent trials (7.0%) compared to target present trials (2.5%). Similarly, when error rates were examined in the three-relevant location condition separately with the factors target contingency (100% and 50% location predictable targets) and target type (present and absent), a main effect of target type was revealed indicating a bias to report “absent”, $F(1, 30) = 47.9$, $p < .001$. In addition, there was an interaction between target contingency and target type indicating a greater increase in error rates across target contingency for target present trials (50%: 8.9% vs. 100%: 6.3%) than for target absent trials (50%: 2.2% vs. 100% 2.7%). The uncertainty about the target location in the 50% predictable location likely caused the number of misses to increase. For target absent trials the direction of this difference reversed between the two conditions, but was not significant. As in Experiment 1 there was no evidence of a speed-accuracy tradeoff in any of the conditions.

3.3 Discussion

In Experiment 2, a two-relevant location condition was pitted against a three-relevant location condition in order to examine whether participants learn the likely locations of targets or only to search a relevant subset of locations. In each condition only two items were ever probed as targets; in the two-relevant location condition each target occupied the same location for all target present trials, whereas in the three-relevant location condition one target occupied the same location for all target present trials, but the other target was presented in one of two different locations. Regardless of whether or not participants were assigned to the two-relevant or three-relevant location condition RTs to 100% location predictable targets were similar, indicating that participants knew the likely location of the target and did not search the among possible target locations – two for the two-relevant location condition and three for the three-relevant location condition. Therefore, it is unlikely that Experiment 1's results were due to participants adopting a strategy of searching through a relevant subset of locations because such a strategy would have resulted in longer RTs to targets in the three-relevant location condition than in the two-relevant location condition regardless of likelihood that a target would appear in a given location.

In the three-relevant location condition RTs to 100% location predictable target were significantly faster than RTs to the 50% location predictable targets. Again, this strongly demonstrates that when the target location was 100% predictable participants knew the likely location of the target and did not check additional locations, whereas for the 50% location predictable target more than one location was checked prior to target verification. I cannot rule out the possibility that when the 50% location probable target was probed, participants first checked the 100% location predictable target location because this location was probed more frequently than the other two locations. It is, therefore, possible that for the 50% location predictable target participants did not learn the two likely locations in which the target might appear.

Finally, evidence of learning can be gleaned from the target absent trials. Unlike, target present trials in which participants learned the likely location of the 100% location predictable target when participants were unsure about whether the target might be present RTs were elevated in the three-relevant location condition compared to two-relevant location condition. In fact, in the three-relevant location condition RTs to target absent trials were equivalent regardless of target predictability, indicating that when the target was absent in this condition participants were checking a similar number of display items before making a ‘no’ response. This indicates that in the three-relevant location condition participants preferred to check at least all possible target locations before responding target absent. RTs to target absent trials for each of the targets in the two-relevant location condition were also equivalent. However, because target predictability was equivalent in this condition and target absent RTs are always longer than target present RTs it is unclear whether participants in the two-relevant location condition were checking only the likely location of the target or were checking both possible target locations. Further, in both conditions participants may have checked additional display locations in which no target ever appeared because of noise from those additional items (for further explanation see Experiment 1). This means that participants did not appear to learn the association between the target present item and its target absent foil. It is possible that learning the likelihood that a target would appear in a particular location exhausted computational resources and, therefore, participants could not extract the association between the target item and its foil.

4. EXPERIMENT 3

Experiment 3 was designed to obtain more direct evidence for learning the association between an item and the location it is likely to occupy in a search paradigm where each location was equally likely to contain a target, but each target was more likely in one location than another. Returning to the kitchen example imagine that my toaster is located on the counter next to the stovetop with greater probability than in the bottom cupboard, if I have learned to extract this regularity then when looking for my toaster I should check the counter next to the stovetop before looking in the bottom cupboard.

In Experiment 3, I sought to replicate and extend the work by Hoffman and Kunde (1999) suggesting that participants could learn the likely location of a particular target. Recall in their experiments, one location contained the target with higher probability than any other location. In addition, this location was more likely to contain one of two targets. Hoffman and Kunde found that not only were participants faster to detect targets in the high probability location than any other, but that this also interacted with the identity of the item in that location. Participants were faster to respond to the target which was more likely to occur in that location than the target which was less likely to occur in that location. However, this pattern of results did not transfer to all locations tested in their study, therefore it was unclear to what degree participants were learning to associate a particular identity to a particular location. In Experiment 3, I sought to clarify these results by examining whether participants could learn the likely location of a target under conditions where the identity-location association could not easily spread across multiple locations and no single location was probed more often than any other removing the possibility that one location was learned better.

I adapted a design used by Geng and Behrmann (2005) to investigate the role of spatial probabilities as an attentional cue in visual search. They presented participants with displays in which a rotated target T and either three or seven rotated distractor Ls were presented around an imaginary circle (set sizes 4 and 8). Participants were asked to report the T's facing direction on each trial. One location was designated the high probability location and the target appeared in that location on 75% of the trials. On the remaining 25% of the trials, targets appeared equally often in each of the low probability locations (three locations for set size four and seven locations for set size eight). Geng and Behrmann found that participants detected targets in high probability locations more quickly than in low probability locations. Further, the search slope for the high probability items was shallower than the search slope for the low probability items, indicating that interference from an increased number of distractors was reduced significantly for items in the high probability location. Thus, Geng and Behrmann showed that spatial probability information could affect search efficiency. However, they could not ask any questions about learning the identity of an item in a location because the target item was always a T, and so identity information was not unique to varying location probabilities.

In Experiment 3 I altered Geng and Behrmann's 2005 design in order to examine whether participants could learn which of two locations was more likely to contain a given target. As in Experiment 2, participants were presented with a ten item display presented around an imaginary circle. Two letters were randomly chosen to be designated the potential targets. Only these two letters were ever presented in the center of the display as target probes. Each of the two target letters occupied one high probability (HP) position for 75% of the target present trials. For the other 25% of the target present trials each of the potential target letters switched locations (to occupy its low probability, LP position). For example, consider a case where “N” and “F” are the targets. As is shown in Figures 9A & B when “N” is probed as the target it appeared in the 12 o’clock position for 75% of the target present trials. Likewise, when “F” was probed as the target it appeared in the 7 o’clock position for 75% of the target present trials. These were the HP locations for each target. However, for 25% of the target present trials when “N” was the target it appeared in the 7 o’clock position and when “F” was the target it appeared in the 12 o’clock position. That is, the letters simply swapped locations; all other items in the display remained unchanged. These were the LP locations for each target. Using this design I could examine whether participants learned to look for the particular target item in its likely location first before checking the other possible target location, that is whether they learned to check at 12 o’clock first when the target was an “N” and 7 o’clock first when the target was a “F”. Further, location effects were controlled; each of the two locations was probed equally often, only the likelihood of finding a particular target in a given location was varied. It was expected that if participants learned the likely location of each target item there would be a processing advantage, resulting in faster RTs, when the target item appeared in its HP compared to its LP location.

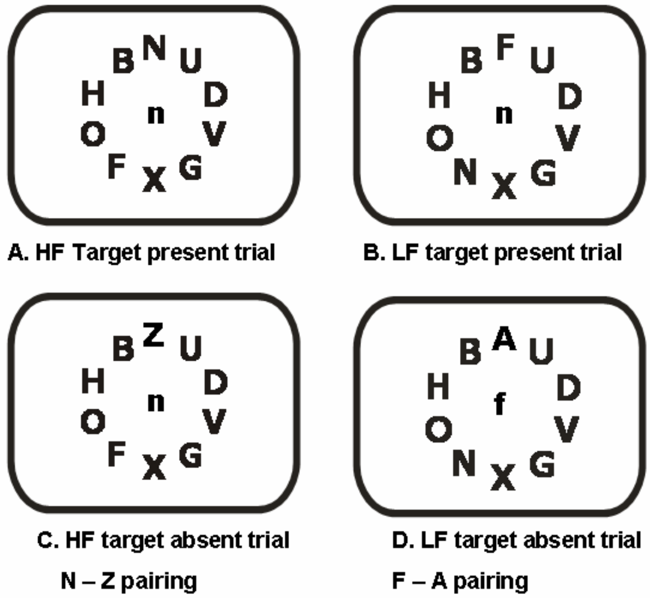

Figure 9. Examples of the display types used in Experiment 3. Top panel depicts target present trials. A. High probability (HP) target present trial with the potential target items “N” and “F”. In this example the “n” is presented at the center as the target probe and the uppercase version of the “N” is located in the display at 12 o’clock. This display was presented for 75% of target present trials. B. Low probability (LP) target present trial. In this example “n” is the target probe and the uppercase version of the “N” is present in the display at 7 o’clock. The “N” and “F” have swapped locations. This display was presented for 25% of the target present trials. Bottom panel depicts target absent trials. C. High probability target absent trial. The “n” is still presented as the target probe, but the uppercase version of the “N” in the display has been replaced by a “Z” in the N’s high probability 12 o’clock location. All other elements of the display were unchanged. The pairing between the “N” and the “Z” remained constant throughout the experiment. D. Low probability target absent trial for “F”. The “f” is presented as the target probe, but the uppercase version of the “F” in the display at 12 o’clock has been replaced by an “A” in the F’s low probability location. All other elements in the display were unchanged. The pairing between the “F” and the “A” remained constant throughout the experiment.

Half of the trials did not contain the target letter. For target absent trials the two letters that had previously been selected as the targets were still presented as probes in the center of the display an equal number of times, but were replaced in the display by a new foil letter, as in Experiment 2. The probability with which foils appeared in each location matched target present trials. Once a target foil item was chosen it was always presented with the same target probe. For example, for a HP target absent trial in which "N" was probed as the target, "N" was replaced in the display at the 12 o'clock position by "Z" and the "F" remained at the 7 o'clock position. For a LP target absent trial in which "F" was probed as the target, "F" was replaced in the display at the 12 o'clock position by "A" and "N" was presented at the 7 o'clock position (See Figures 9C & D). If participants learned the target-foil association, RTs should be faster in HP than LP locations. In Experiment 2 participants did not learn the target-foil association (at least in the three-relevant location condition); Experiment 3 allowed me to further examine whether participants could learn the target-foil pairing. In order to increase the likelihood that participants would extract this regularity I increased the total number of trials.

4.1 Method

4.1.1 Participants

Thirty participants (19 F) were recruited from the University of Arizona and either received course credit or $10 for their participation. All subjects had normal or corrected-to-normal visual acuity. An additional four participants (1 F) were excluded for exceeding the error criterion.

4.1.2 Stimuli and Apparatus

All the stimuli were created in the same manner as Experiment 2 except for the following changes. Ten letters were randomly chosen to occupy the positions on the invisible circle. This display was the high probability display. Two probe items were selected from amongst the 10 display items with the rule that each item was separated by at least three intervening items. These two items served as the target probes for the entire session for an individual subject. A low probability display was created by swapping the two target items' locations (see Figures 9A & B). Four target absent displays were also created: two from the high probability and two from the low probability displays. High probability target absent displays were created by replacing one of the target items with a randomly chosen new foil item that had not previously been presented. Only one item, the target item, changed in each display. Two additional target absent displays were created from the low probability display in the same manner (Figures 9C & D). This pairing between the target present item and the foil was consistent for all target absent trials. Four different sets of letters were chosen and from them four different programs were created. Program order was counterbalanced across participants to ensure that results were not specific to particular locations or identities. In addition, there were no apparatus changes.

4.1.3 Procedure and Design

The procedure and design emulated Experiment 2 in all respects except for the following. Each participant performed 6 blocks of trials each containing 64 trials for a total of 384 trials. A large number of trials allowed for the examination of the time course of the learning. Each block contained the following conditions: 48 HP trials with each of two targets probed equally often (24 trials each), 16 LP trials with each of two targets probed equally often (8 trials each). On all trials only two targets were presented as probes. Each target was presented equally often. Half the trials were target present trials and the other half were target absent trials on which the target's foil replaced it in the display. Trials were presented randomly within each block. Participants were given two breaks (after blocks 2 and 4). Each break had a mandatory rest period of 5 sec, but participants could rest as long as they wanted before recommencing the experiment. The experiment lasted approximately 45 minutes.

4.2 Results

Mean correct RTs were calculated for each condition in each block. RTs that were more than two standard deviations from the individual's condition mean were excluded. This resulted in the elimination of 1.5% of the data.

Participants were faster to respond on HP (847.2 ms) than LP (871.1 ms) trials regardless of whether or not the target was present (see Figure 10 and Table 2). A repeated measures analysis of variance (ANOVA) with the factors: condition (HP and LP), target type (present and absent) and block (1 – 6) showed a main effect of condition, $F(1, 29) = 24.9$, $p < .001$. That is, participants checked the item's HP location before to its LP, indicating that they had learned the likely location of each item and used that knowledge to decrease their RTs to report target presence or absent. As in previous

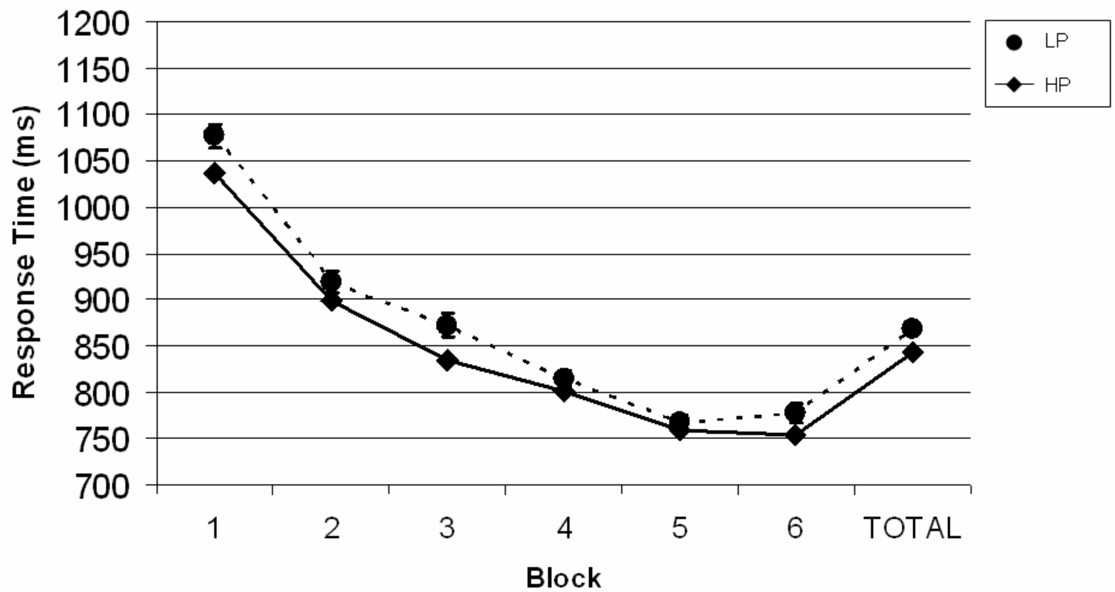

Figure 10. Experiment 3 mean RTs for HP compared to LP trials across blocks [collapsed across target type (present and absent)]. HP trials depicted with the solid line. LP trials depicted with the dashed line.

Table 2. Experiment 3. High probability and low probability mean RTs across block.

Experiment 3	Block						
	1	2	3	4	5	6	TOTAL
HP	1035.9	898.6	835.2	800.7	759.1	753.6	843.3
	(35.7)	(31.9)	(30.4)	(28.2)	(29.6)	(31.1)	(27.8)
LP	1076.9	918.5	872.4	814.4	767.3	776.9	868.2
	(31.5)	(33.3)	(34.7)	(29.4)	(28.9)	(29.4)	(27.5)
DIFF	-41.0	-19.9	-37.2	-13.7	-8.2	-23.3	-24.9
	(12.5)	(11.8)	(12.8)	(8.8)	(9.0)	(9.9)	(4.9)

Notes: Standard errors are in parentheses. HP = high probability. LP = low probability.

DIFF = Difference between HP and LP.

experiments, RTs to target absent trials were longer than RTs to target present trials, $F(1, 29) = 123.6$, $p < .001$. The ANOVA also showed a main effect of block, $F(2.4, 70.8) = 60.8$, $p < .001$ (corrected by Greenhouse-Geisser due to a violation of the assumption of sphericity) showing that in all conditions participants RTs decreased with block number, due to practice on the task and experience with the display. There was also an interaction between target and block, $F(5, 145) = 18.4$, $p < .001$, indicating that the reduction in RTs across block was smaller for target present than target absent trials. However, there was no three-way interaction between condition, block and target that might have indicated differences in learning rates across target type as might have been expected given that participants in Experiment 2 did not learn the target-foil associations. Planned comparisons to examine when learning first emerged showed that differences among the critical HP and LP conditions were already apparent by the end of block 1, $t(29) = 3.2$, $p < .005$, one-tailed, this difference remained robust across the first 3 blocks of trials, $ts > 1.7$, $p = .05$, one-tailed. In block 4 the effect was marginal, $t(29) = 1.6$, $p = .07$, one-tailed and disappeared entirely in block 5. Finally, the effect reemerged in block 6, $t(29) = 2.4$, $p < .05$, one-tailed.

Finally, an ANOVA was conducted on error rates with the factors: condition (HP versus LP), target type (present and absent) and block (1 – 5). More errors were made on target present trials (5.6%) than on target absent trials (1.9%), $F(2, 38) = 10.7$, $p < .001$. Again, indicating a bias for participants to say “absent” as is common in the search literature. There was also a main effect of block (corrected for a violation of the assumption of sphericity by Greenhouse-Geisser), $F(4, 76) = 5.3$, $p < .001$, signifying that error rates decreased as blocks increased. There was no evidence of that error rates were higher on the HP trials (3.6%) where RTs were faster than to the LP trials (4.0%), $F < 1$ and thus, no evidence of a speed-accuracy tradeoff in this critical comparison.

4.3 Discussion

In Experiment 3 I obtained evidence that participants can learn the likely locations of two target items and their respective foils. RTs were faster for HP than LP trials indicating that participants checked the HP location for a particular item before the LP location. Targets were equally likely in each of the two locations, only target identity predicted which location was more likely. Therefore, participants were able to extract the relative probability with which a target was presented in each location. In addition, the HP – LP difference emerged as early as block 1, indicating that this learning can occur rapidly (i.e. after each target appeared 12 times in its HP location).

Learning was most robust in blocks 1 -3, dissipated in later blocks, and reemerged in the final block. It is not clear why this happened, but one possibility is that over the course of learning participants may have adopted a strategy of distributing their attention more widely in order to place a “spotlight” of attention over the two locations in which they had learned that targets were likely to appear. Over time this strategy may have proved to be computationally costly because spreading attention to encompass the two target locations would mean that other distractor items would also be within the spotlight of attention. [It is unclear whether or not participants could split this attentional spotlight and/or ignore these intervening distractors (e.g. Cave & Bichot, 1999; Eriksen & Yeh, 1985; Kim & Cave, 1995; Posner, Synder, & Davidson, 1980).] Because of this cost participants might have reverted back to using their knowledge about the likely location of each target, in fact the HP-LP difference reemerged in block 6.

In Experiment 2 participants did not demonstrate learning of the target-foil association, at least in the three-relevant location condition. In contrast in Experiment 3 participants not only learned the association, but learned as quickly on target absent trials as target present trials. One possible reason for this difference is that the variability caused by uncertainty about where the 50% location predictable target would occur (because it was equally likely in each of two possible locations) was enough to prevent learning of the target-absent foils because the visual system continued to monitor that target item to a greater degree in order to be sensitive to any information indicating a single likely location for that target and this exhausted computational resources.

I also examined whether the HP-LP difference presented above was actually due to trial-to-trial repetition priming rather than learning the likely location of the target. Because targets only ever occupied two locations strings of identical 1-back trials could occur repeatedly. Repetition priming effects were defined as trials in which both the probe and the display matched on trial n and trial n-1. For example, a repeated target present trial was defined as one in which the letter “N” was probed as the target and was located in the display at 12 o’clock across trials n and n-1. In contrast, a repeated target absent trial would be defined as one in which the letter “N” was probed as the target and its foil, “Z” was located in the display at 12 o’clock across trials n and n-1. Trial-to-trial repeats occurred at a rate of 16.5% for HP trials compared to 4.6% on LP trials. (These rates collapse across target present and absent trials as the rates were similar for each target type.) A posthoc analysis was done in which all 1-back repeated trials were eliminated. RTs were still faster to HP than LP trials, $F(1, 29) = 106.6$, $p < .001$, indicating that participants were learning the likely locations of target items over and above any effects that might have been due purely to repetition priming. The relationship between learning the likely locations of targets and other types of probability learning and repetition priming are considered further in the General Discussion.

5. EXPERIMENT 4

The convergence of evidence in Experiment 1 - 3 clearly shows that participants can learn to associate items with locations where they were highly likely to occur. Thus, showing that there is memory in repeated search and that participants use this memory to locate target items more quickly. Further, Experiment 1 demonstrated that even under conditions where learning effects were observed search slopes were positive across increases in display size. Therefore, positive search slopes cannot be taken as evidence for memory-free search, as has been argued by Wolfe and colleagues (2000). Recall, that one potential hypothesis for positive search slopes despite learning is that there is competition among display memories. When a repeated display is seen following learning memories for the display are reactivated, these reactivated memories compete, and competition takes time to resolve. Experiments 1-3 have established that memory for the display includes the location of the target item and the relative probability with which the item occurs in a location. In Experiment 4 I investigated whether participants also learn the direction to the target. Recall that each trial begins with a fixation cross so that participants start their search from the same location, the center of the imaginary circle. Therefore, participants may learn the direction from fixation in which the target is likely to be located and these direction vectors may get incorporated into memory for the display. (For the purposes of this paper a direction vector simply codes for the direction from fixation to the target on a trial in which successful target detection has occurred.)

Learning direction vectors may be one way in which memory for the likely location of a target gets instantiated.

There are two frames of reference in which the likely location target may be coded: allocentric or egocentric. Allocentric coding refers to a spatial reference frame which is independent of the observer's position and instead relies on the relative positions of objects or other environmental features. For example, if learning was allocentric participants would have coded the “B” as adjacent to the “H”. In contrast, egocentric coding refers to a spatial reference frame that is dependent on the observer's position. That is, spatial information maintains the perspective under which it has been experienced. For example, if learning was egocentric participants learned that the “H” was to the 45° to the left of their fixation. If participants learned the likely location of the target by encoding directional vectors then learning was egocentric. Experiment 4 explores this possibility.

Chun and Phelps (1999) tested amnesic patients with hippocampal damage on the contextual cueing task used by Chun and Jiang (1998; see Figure 3 and the discussion in section 1.1). The amnesics learned to find the target more quickly across blocks, demonstrating that they could benefit from general experience with the search task. However, they did not learn the contextual cueing information: RTs for “old” versus “new” displays were equivalent. Chun and Phelps argued that the hippocampus (impaired in amnesics) was needed for contextual cueing. This may support an allocentric learning interpretation of Chun and Jiang's results as it is argued that the hippocampus binds multiple cues using allocentric rather than egocentric information (e.g. Holdstock, Mayes, Cezayirli, Isaac, Aggleton, & Roberts, 2000; O'Keefe & Nadel, 1978). However, because participants started each trial with a fixation cross in the experiments presented here they may have been biased to code the displays egocentrically, with respect to direction from fixation.

Experiment 4 examined the role of memory for the direction vectors by changing the location of the fixation cross and thus, changing the direction to locate the target following training. Experiment 4 used a design that was identical to that used in Experiment 3, except that following a training block the location of the fixation cross changed. This design allowed me to investigate whether or not subjects learned the direction (egocentric coding) to the target because the absolute locations (allocentric coding) of the display items were held constant. To the extent that direction to the target had been learned then changes in the starting point of the search will disrupt this memory, at least temporarily.

5.1 Method

5.1.1 Participants

Thirty participants (15 F) were recruited from the University of Arizona and either received course credit or $10 for their participation. All subjects had normal or corrected-to-normal visual acuity. An additional, seven participants (4 F) were excluded as a result of either exceeding the error criterion (N = 4, 2F) or because they made no correct responses in at least one condition in a given block (N = 3, 2F). Eleven participants (8F) had their eye movements monitored to ensure that they were looking at the fixation cross at the start of each trial. All remaining participants made a self report that they had started each trial by looking at the fixation cross.

5.1.2 Stimuli and Apparatus

Stimuli and apparatus were the same as used in Experiments 3 except for the following changes. A head-mounted infrared-based eye tracker, model 400SU (Applied Science labs, Bedford, MA) was used to monitor eye movements. The head tracking system relies on Ascension Technologies Flock of Birds technology, which corrected for online head movements made by the participant. This system records from the pupil and cornea at a rate of 60 Hz with measurement accuracy of greater than 1° of visual angle.

Creation of the search displays emulated the method used in Experiment 3 using new randomly selected letters. Four programs were created and program order was run in a counterbalanced order across participants. The two target items were chosen with the rule that only one or two items were located between the two targets. For two of the four programs there was only one intervening item so that the distance from each fixation cross and each target was equated. That is, for these displays the distance from the central fixation and the distance from peripheral fixation cross to each of the targets was equal (see Figure 11A). For the other two programs there were two intervening items between the two target locations, for these displays the distance from the central fixation cross to each of the targets was equal, but shorter than the distance from the peripheral fixation cross to each of the target. The distance from the new fixation to each of the targets was equal, however (see Figure 11B). These two types of displays were used in order to: (1)

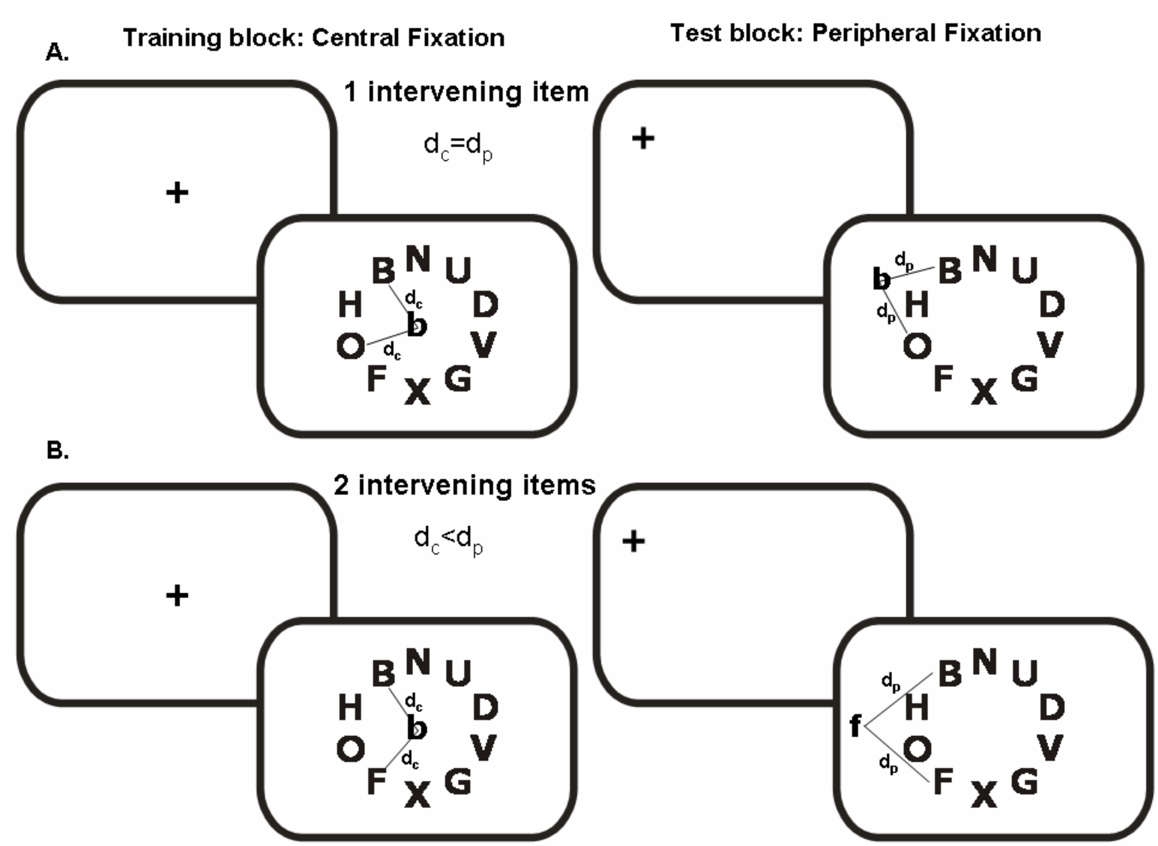

Figure 11. Examples of the displays used in Experiment 4. The left panel depicts training trials in which the central fixation cross is presented, whereas the right panel depicts the test trials in which the fixation cross has been moved to a peripheral location. The top panel depicts displays in which there was only one intervening item between targets. Only HP trials are presented for the targets: "o" and "b". Lines drawn from the central fixation location to the targets indicate that that distance from the fixation to each target is equivalent $d_c = d_c$, where c = central. In addition, lines from the peripheral fixation location to the targets are also equivalent $d_p = d_p$, where p = peripheral. Finally, in this condition the distance between $d_c = d_p$. The bottom panel depicts displays in which there were two intervening items between targets. Only HP trials are presented for the targets: "o" and "f". Lines drawn from the central fixation location to the targets indicate that that distance from the fixation to each target is equivalent $d_c = d_c$. In addition, lines from the peripheral fixation location to the targets are also equivalent $d_p = d_p$. However, in this condition $d_c < d_p$.

Examine whether HP-LP differences were diminished in the one-intervening item condition compared to the two-intervening item condition because participants immediately adopted a strategy of spreading their attention across the two locations when only one additional item intervened rather than make use of the statistical likelihoods of a target occurring in a particular location. When two targets are placed closely together this strategy may be less computationally costly. (2) Equate the fixation location to target distance in at least one condition; if RTs increase when the fixation location is moved only the two-intervening item condition this could be due to the increased distance from the new fixation location to the targets in this condition compared to the one-intervening item condition where the distance from the original fixation location to the targets was shorter. Participants always trained on the central fixation cross first because this was the only location in which the distance from the fixation cross to all ten display items is equal.

5.1.3 Procedure and Design

The procedure and design emulated that used in Experiment 3 except for the following changes. There were eight mini-blocks for each fixation location (16 total blocks), each contained 16 trials for a total of 256 trials (four mini-blocks equated to the same number of trials as one full block in Experiments 2 and 3). Each mini-block had the same proportion of trial types as each block of Experiment 3. The number of trials per block was reduced because even if changing the starting point of the search disrupts learning, participants may be able to either remap the direction to the targets with a small number of trials, do a simple computational translation to convert the original direction vector to the new direction vector, or switch to relying on allocentric coding (participants may code the display in both allocentric and egocentric coordinates). This design would allow for a sensitive measure of the degree of disruption in the learning pattern. The fixation cross was placed at the center of the display for the first eight mini-blocks. Then there was a break and a new set of instructions informing participants that the starting point of the search would change and the fixation cross would be positioned in a new peripheral location. As in the first half of the experiment participants were asked to look at the fixation cross at the start of each trial. The fixation cross was moved to a peripheral location for the last eight mini-blocks. Two additional breaks were given after the fourth mini-block in each fixation condition. The first 11 participants (8F) had their fixation monitored. For these participants the experimenter initiated the start of each trial after ensuring that were looking at the fixation cross. The remaining participants did not have their eyes monitored due to problems with the equipment. These participants were instructed to center their eyes on the fixation cross before initiating the trial with a foot pedal press. For more on this issue see the discussion following Experiment 4.

5.2 Results

Mean correct RTs were calculated for each condition (HP and LP), target type (present and absent) and fixation location (central and peripheral) in each block. RTs that were more than two standard deviations from the individual's condition mean were excluded. This resulted in the elimination of 1.3% of the data.

A mixed measures ANOVA was run with the within subjects factors condition (HP and LP), target type (present and absent), fixation location (central and peripheral) and block (1-8) and the between subjects factors eye-movement monitoring and target position (1 intervening item and 2 intervening items) to evaluate any differences due to the between subjects factors. There were no main effects of eye-movement monitoring or target position, nor any interactions with these grouping factors, indicating that behavior was similar regardless of whether or not participants had their eye movements monitored and whether or not the distance from the fixation cross to the targets was equal for the central fixation location compared to the peripheral fixation location. Therefore, these between subject factors will not be considered in further analyses.

An ANOVA conducted on the central fixation condition with the factors: condition (HP and LP), target type (present and absent), and block (1-8) demonstrated that Experiment 4 replicated Experiment 3. Participants were faster on HP than LP trials as indicated by a main effect of condition, $F(1, 29) = 13.3$, $p =.001$ (see Figure 12 & Table 3). In addition, as expected participants were faster to respond present than absent, $F(1, 29) = 97.8$, $p < .001$. Also, as in previous experiments there was a practice effect indicating faster RTs across blocks, $F(3.2, 92.7) = 32.9$, $p < .001$, corrected by Greenhouse-Geisser for a violation of the assumption of sphericity.

I evaluated whether participants learned the direction from fixation to the likely target location by comparing the last block of the central fixation to the first block of peripheral fixation. These two blocks were chosen because: (1) General practice effects across blocks would obscure any changes in fixation location alone if assessed in an omnibus ANOVA. Recall that all participants trained on the central fixation location and

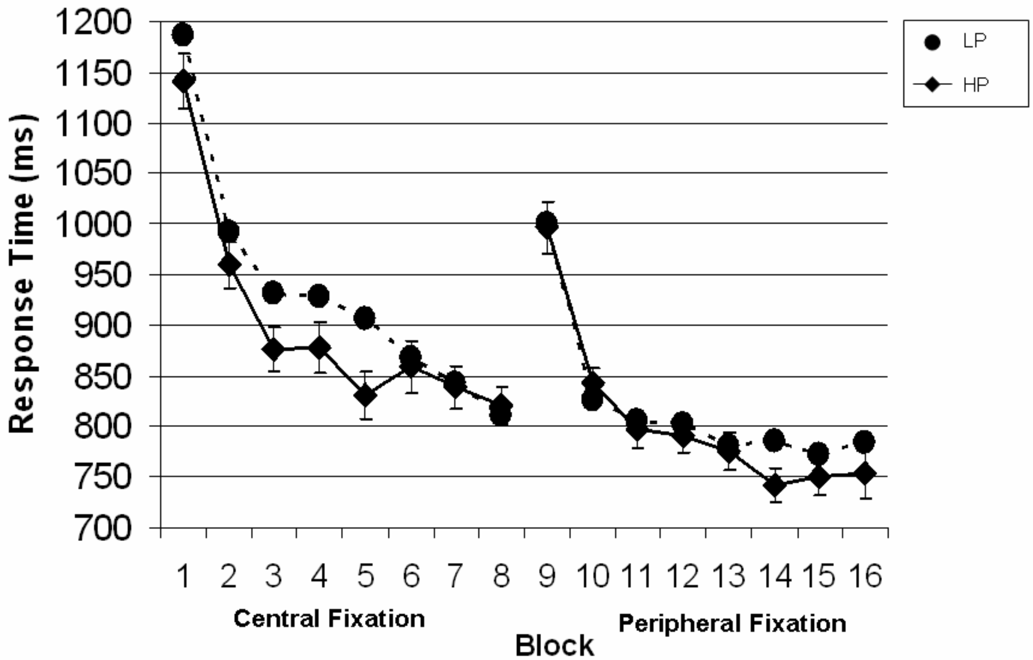

Figure 12. Experiment 4 mean RTs for HP compared to LP trials across blocks [collapsed across target presence (present and absent)]. HP trials depicted with the solid line. LP trials depicted with the dashed line. Blocks 1-8 depict training with the central fixation cross. Blocks 9-16 depict test with the new peripheral fixation cross.

Table 3. Experiment 4. High probability and low probability mean RTs across fixation location conditions by block.

Experiment 4 Central Fixation	Blocks							
	1	2	3	4	5	6	7	8
HP	1141.4	959.3	876.7	878.0	830.4	859.0	838.9	820.8
	(40.2)	(37.2)	(33.9)	(34.5)	(29.2)	(30.5)	(29.4)	(26.5)
LP	1185.9	992.7	932.2	927.6	906.7	867.0	843.4	811.4
	(50.1)	(42.6)	(39.7)	(39.9)	(42.3)	(40.1)	(30.3)	(28.7)
DIFF	-44.5	-33.4	-55.5	-49.6	-76.3	-8.0	-4.5	9.4
	(26.9)	(22.1)	(21.8)	(24.9)	(23.9)	(25.9)	(20.7)	(19.1)
Peripheral Fixation	Blocks							
	9	10	11	12	13	14	15	16
HP	996.3	841.9	796.6	790.4	776.0	742.0	750.1	754.0
	(24.7)	(27.2)	(25.1)	(21.2)	(27.6)	(25.7)	(26.4)	(21.9)
LP	1000.0	826.5	806.0	802.5	780.0	785.8	772.1	784.0
	(36.1)	(31.4)	(25.5)	(26.0)	(26.6)	(31.5)	(29.6)	(35.3)
DIFF	-3.7	15.4	-9.4	-12.1	-4.0	-43.8	-22.0	-30.0
	(26.6)	(16.1)	(17.2)	(17.0)	(18.3)	(16.5)	(18.7)	(24.7)

Notes: Standard errors are in parentheses. HP = high probability. LP = low probability.
DIFF = difference between HP and LP.

only after training did the location of the fixation cross change. Participants RTs decreased across blocks and the peripheral fixation was presented only in that last eight blocks. Therefore, if fixation location were examined across all trials any disruption due to changing the direction to the target would be contaminated by a general decrease in RTs due to practice. Two consecutive blocks were chosen to equate for practice effects. The last block of the central fixation was chosen in order to ensure that participants had a fair amount of time to learn the display. (2) It was possible that the change in fixation would only disrupt learning for a short period of time because participants would relearn the direction in which the target could be located quickly, perform a simple computational translation to convert the original direction vector into the new direction vector or switch to relying on allocentric coding. Therefore, the first block of the peripheral fixation was used for comparison to the central fixation. An ANOVA with the factors fixation location (last block central and first block peripheral), condition (HP and LP) and target type (present and absent) showed that participants were slower to respond to targets in the new fixation location (998.2 ms) than in the original fixation location (816.1 ms), indicating that participants have learned the direction from the fixation cross in which they are likely to locate the target $F(1, 28) = 41.9$, $p < .001$ (see Figure 12 and Table 3). In addition, this ANOVA showed the typical target type effect, RTs to target present trials were faster than to target absent trials, $F(1, 28) = 62.9$, $p < .001$. There was no main effect of condition, $F < 1$, indicating that RTs were no longer faster to HP than LP targets. One reason this might have occurred is that over the course of learning participants adopted a strategy of distributing their attention over the two locations in which they learned the target would appear and so HP and LP effects were eliminated (see Experiment 3, section 4.3 for further discussion of this possibility). Because there was no interaction between fixation location and condition I cannot attribute the failure to observe a HP-LP effect to a change in the direction to the likely target. A second ANOVA examining whether change in fixation location effects could still be observed in the second block of peripheral fixation conducted with the factors fixation location (last block central and second block peripheral) and target type (present and absent) showed that the difference in RTs across fixation location had already disappeared, $F < 1$ at this point. After 16 trials RTs to targets in the peripheral fixation condition are equivalent to RTs observed in the central fixation condition.

Finally, an ANOVA was conducted on the new peripheral fixation condition separately, in order to investigate the role of continued learning. Recall, that in both Experiment 3 and some of the blocks of trials evaluated in Experiment 4 (and presented above) the difference between the HP and LP locations disappeared. I have hypothesized that this may be due to a change in strategy whereby participants spread their attention across multiple locations for some period of time after learning the likely locations of the targets. In Experiment 3 the HP-LP difference reemerged indicating that participants began to use their knowledge about the likely location of the item again, possibly because spreading attention was computationally costly because intervening items could not be ignored. An ANOVA with the factors: condition (HP and LP), target type (present and absent) and block (9-16) revealed that participants were significantly faster on HP than LP trials, $F(1, 29) = 5.0$, $p < .05$, in the peripheral fixation condition. In addition, participants were faster to target present than target absent trials, $F(1, 29) = 71.0$, $p < .001$, and also demonstrated a general practice effect as RTs decreased across blocks, $F(4.2, 122,8) = 33.2$, $p < .001$, corrected for a violation of the assumption of sphericity by Geisser-Greenhouse. This indicates that, as in Experiment 3, despite the fact that learning effects changed over time, when learning was examined across all peripheral fixation location trials there was evidence that participants checked the likely location of the target (HP) before the unlikely location (LP).

As in the previous experiments error rates were low (3.0%). An ANOVA was conducted on error rates for the central fixation condition with the factors condition (HP and LP), target type (present and absent) and block (1-8). There was only a main effect of target that indicated, as in previous experiments, a bias to report absent (5.4%) compared to present (2.0%), $F(1, 29) = 23.8$, $p < .001$. A repeated measures ANOVA conducted on error data across the critical last block of the central fixation location and first block of the peripheral fixation location indicated a main effect of target, again participants were biased to say absent (3.6%) compared to present (1.1%), $F(1, 29) = 4.7$, $p < .01$. There was no evidence of a speed-accuracy tradeoff which might have accounted for the differences in the RT data in the critical fixation location condition. Finally, an ANOVA conducted on the error data from the peripheral fixation condition alone revealed no significant main effects or interactions. One potential explanation for this is that participants already had eight blocks of central fixation prior to the peripheral fixation condition and, therefore may have had enough practice on the task for errors rate to be at floor. Overall error rates in this block were 2.4%.

5.3 Discussion

In Experiment 4 I obtained evidence that participants were learning the likely direction from the starting point of the search, in this case the fixation cross, to the target location. Participants' search times were disrupted for at least one block of 16 trials following the change in the fixation location. This provides preliminary evidence that when participants start their search from the same location on every trial that learning may be coded egocentrically. This is because only the direction to the target from fixation was changed following training and this type of information is coded egocentrically. In contrast, the absolute locations of the items in the display, information which underlies allocentric coding, remained constant throughout the experiment. Further, these direction vectors may be one possible mechanism for learning the location of a target. For example, the target probe letter may get incorporated into memory with the direction vector which would provide the likely location of a given target.

I obtained slower RTs to trials in which the fixation location changed for the first block of peripheral fixation compared to the last block of central fixation. However, because there was a change in the display there is an alternative explanation which is that participants RTs were slower to the new fixation location trials because of a surprise effect. I argue that this difference is due to participants having learning the direction from fixation to the target because measures were taken to ensure that the role of surprise would be reduced in this experiment. Following the training block a new set of instructions appeared on the screen notifying participants that the fixation cross would now be located in a new position and that as before on each trial they needed to look at the fixation cross before starting the next trial. They were also informed that all other aspects of the experiment would be the same as during training and therefore, knew where to expect the display items to appear. In addition, the experiment was self-paced, so when the fixation cross appeared in the new location participants could take as much time as needed before pressing the foot pedal to initiate the trial. Unfortunately, because the difference between HP and LP trials disappeared during the last block training with central fixation I could not examine the effect of the peripheral fixation on this aspect of learning. Recall that in both Experiments 3 and 4 the difference between HP and LP trials emerged early, dissipated during the middle blocks, and reemerged late. A future experiment could examine whether HP-LP learning is disrupted by changing the direction to the target by either reducing the number of training trials so that participants are still demonstrating the HP-LP effect at the end of the central fixation condition or by increasing the number of training trials, so that the HP-LP effect has reemerged prior to moving the fixation location.

There were two target position conditions (1 or 2 intervening items between the targets) in this experiment. This was done in order to (1) Examine whether HP and LP difference disappeared when only one item intervened between the two target items because participants adopted a strategy of spreading their attention across the locations. (2) And evaluate whether the increased eccentricity of the items from the peripheral fixation to the target in the two-intervening item condition than in the one-intervening item condition slowed the participants in addition to the change in fixation location alone. No differences were obtained due to either of these grouping factors, indicating that participants in each of the conditions adopted similar learning strategies. In addition, greater eccentricity in the two-intervening compared to the one-intervening item conditions did not change RTs, indicating that differences across the fixation location conditions were not simply due to the increase in the distance to the targets when the fixation cross was in the peripheral location rather than learning the likely direction to the target from fixation. However, even in the case of two intervening items between the targets the difference in the distances between the central fixation and the targets and the new fixation and the targets was small, had the number of intervening items been even greater eccentricity may have affected performance.

In Experiment 4 the first 11 participants had their eye movements monitored to ensure that they started each trial by looking at the fixation cross. Remaining participants did not have their eyes monitored, but all made a self-report that they looked at the fixation cross at the start of each trial. This was important because in order to evaluate whether participants learned direction vectors it was imperative that all participants started each trial at the same location, so that direction information was consistent across trials and only changed following training. Given that no differences were observed between these two groups of subjects it is likely that subjects did, in fact, comply with the instructions and looked at the fixation cross on a majority, if not all of the trials. Had participants not done this I would have expected no differences between the original fixation location and new fixation locations in the critical blocks. Scan paths were not recorded because participants only made a small number of eye movements in this experiment. No participant continued to make eye movements throughout the task.

Therefore, eye movements are not necessary to instantiate this learning. This means that a motor program instantiated by a saccade was not necessary to observe our effects.

Finally, I would like to raise one potential hypothesis regarding how learning direction to the target from fixation occurs. While it is clear that eye movements were not necessary for this learning it is possible that participants moved their attention to the target location to verify its presence. (However, recall that one caveat of these experiments is that I cannot evaluate whether participants were actually making attention movements to target locations or that target located were simply given greater attention weight. (For more on this see Experiment 1's discussion, section 2.3) Further, in as much as an attentional movement is an ingredient of action it is possible that it is the action taken as part of the target verification process that is important for allowing direction vectors to get encoded into memory. For further explanation regarding this possibility see the General Discussion.

6. GENERAL DISCUSSION

Several components of learning across a repeated visual scene were examined in the experiments presented here with the goal of taking significant steps towards resolving the polemical debate about memory in search. Recall, that Wolfe and colleagues (2000) argued that participants continued to search through a repeated display because search slopes remained positive across hundreds of trials. He posited that if participants used memory in the task then search slopes should have approached zero because participants could move their attention directly to the target. In contrast, I hypothesized that participants were able to extract a great deal from repeated search displays, including memory for the location of an item, the relative probability with which a target appears in a particular location, and the direction from fixation in which one is likely to locate a target. Further, employing positive search slopes as evidence that participants rely on vision rather than memory is a flawed logical argument. RTs to verify target presence can rely on a number of factors, including competing memories about the display, rather than simply the number of display items or target/distractor similarity. Indeed, the experiments presented here provided evidence that there was ample memory in a repeated search task, even when positive search slopes were also observed.

In Experiment 1, I demonstrated that RTs to verify target presence were dictated by the number of probed items in the display rather than by the total number of display items. Two conditions were compared: a display set condition in which all of the items in a display (2, 3, 5, or 8) were probed equally often and a relevant set condition in which eight items were always presented but a smaller subset (2, 3, or 5) were probed equally often as targets. If there were no memory in a repeated search task it would be expected that search slopes should be approximately zero in the relevant set condition because participants would continue to search through all eight display items regardless of the fact that fewer items were probed as targets. However, search slopes across these two conditions were similar, indicating that participants did not search through all of the items in the relevant set condition. Instead if only two items were probed RTs were similar to a condition in which only two items were ever presented in the display. I argue that participants were learning the likely location of each target item. Further, these results demonstrate that a reliance on positive search slopes as an indication of memory-free search is not possible. As the number of probed items increased, so did RTs despite the fact that participants were clearly learning about their display and not searching through all eight items. However, there was an alternative explanation for these data that participants were merely learning to search a subset of the display. That is, participants may have been performing visual search on a reduced number of locations. Other studies using visual search as a paradigm have shown that participants can limit their search based on the likely locations in which the target might be found (e.g. Palmer, 1994, 1995). However, these studies used a priming paradigm to cue participants about the likely locations in which the target might occur. The learning in Experiment 1 is different in that it requires participants to integrate information about the likely location of targets across trials without the aid of explicit cues.

In Experiment 2, I sought to eliminate the possibility that participants were searching through a subset of the relevant set display by comparing conditions in which the number of unique target items was held constant at two, but the number of locations in which the target could be located was varied (two-relevant locations compared to three-relevant locations). In the two-relevant location condition each of the two target items were positioned in locations that remained constant throughout the experiment (each target was 100% location predictable when present). In the three-relevant location condition one of the target items was positioned in a location that remained constant throughout the experiment (100% location predictable target when present), but the other target item was found with equal regularity at one of two locations (50% location predictable target when present). If participants were not learning the likely location of items in this experiment, but instead were searching among all the relevant locations then RTs to the 100% location predictable targets should have been longer in the three-relevant location condition than in the two-relevant location condition. This was not the case, rather RTs were similar in both conditions for the 100% location predictable target, indicating that participants learned the likely location in which those targets would appear. There was no evidence that participants were searching through two versus three locations. In addition, RTs in the three-relevant location condition were longer for the 50% location predictable target than for the 100% location predictable target. This indicates that participants learned the location of the 100% location predictable target, but for the 50% location predictable target on some number of the trials participants had to evaluate at least two locations. However, it is possible that participants did not learn the likely locations of the 50% location predictable target because a target occupied each of its potential locations less often than a target occupied the 100% predictable target location, therefore, participants may have always checked the 100% predictable location first when the 50% location predictable target was probed. Finally, when RTs were averaged across all targets regardless of target-location predictability in each of the two conditions there was evidence of a positive search slope; again demonstrating that a positive search slope cannot be taken as evidence for memory-free search.

Experiment 3 was designed to obtain more direct evidence for learning the association between an item and the location it is likely to occupy. However, in Experiment 3, unlike in Experiment 2, each of two locations was equally likely to contain a target, but each target was presented with a higher probability in one location than another. Each target appeared in a HP location on 75% of target present trials. For the remaining 25% of target present trials the targets swapped locations (LP location). For instance, if the targets were “N” and “F” located at 12 and 7 o’clock, respectively for HP trials then for LP trials “N” and “F” swapped locations and appeared at 7 and 12 o’clock, respectively. RTs were faster on HP than LP trials, indicating that participants checked the target’s HP location before checking its LP location. These differences also indicate that participants were able to extract the relative probability with which an item appeared in a location. Further, these effects emerged early, a difference between HP and LP trials occurred as early as the first block after participants performed a mere 64 trials.

Finally, in Experiment 4 I examined a potential mechanism by which these memories may be instantiated, learning direction vectors. Participants learned the likely direction from the fixation cross in which to verify target presence. After training blocks in which participants started each trial at a central fixation point, the starting point of the search was moved to a new peripheral location. This disrupted participants' ability to verify target presence as RTs increased in this condition compared to when the fixation cross was presented in the central location. One way in which participants may have to associate the target with its likely location in the display is by incorporating these direction vectors learned during the target verification process into memory. When the direction of the vector was changed memory for the display was disrupted.

6.1 Competition Hypothesis

Why do RTs often increase as the number of display items increase, despite evidence that participants can learn a great deal about a repeated search display? One possible explanation is that competition exists among display items and the time it takes to resolve this competition determines RTs. Most researchers agree that factors such as target/distractor similarity, distractor/distractor similarity, and the number of display items affects RTs (e.g. Duncan & Humphreys, 1989; Wolfe, 1998). The experiments presented here have added to this list memory for previous experiences with the display. The contribution of competition to RTs varies depending on a number of additional factors such as the number of times a particular target or location has been probed, the relative probability with which an item has appeared in a particular location, the learned direction from the starting point of the search to the target location, to name a few. As a repeated search display is learned memory for these factors gets established and when the display is next seen these memories are reactivated and compete. This competition process takes time and thus, can produce positive search slopes that have been interpreted as evidence for memory-free search.

Competition provides a possible explanation for positive search slopes despite learning, but there are still some remaining questions. Given that participants learned the search displays, one might argue that the top-down information provided by the target probe should have been enough to eliminate or at least allow for the rapid resolution of competition. If this were the case one would also expect to observe shallower search slopes than would be expected with displays in which no learning has occurred and the experiments presented here provide no evidence of that. In Experiment 1 where the design allowed me to examine search slopes there was evidence of positive search slopes (target present search slopes were approximately 30 ms/item) that was of similar magnitude to what one would expect using non-repeated search displays where no learning could occur (e.g. Wolfe et al., 2000; unrepeated search condition slope=35 ms/item). Top-down information given by the target probe is only one component that contributes to the activation or weights of the items in the display. Given all the other information that has been shown by the experiments presented here to contribute to the target verification process it still takes time for the location of a particular target to win the competition. I argue that because so many factors contribute to the total time needed for target verification, a single factor is not enough to reduce the competition to a great enough degree that time taken to verify target presence is reduced. That is not to say that the information provided by the target probe does not bias the competition at all on a particular trial; in fact it is likely to contribute to the assignment of greater attentional weight to the correct target location. However, given that in all of these experiments each target is probed an equal number of times no single item can win the competition based on its identity alone and therefore, any boost in activation given by the target probe alone is not sufficient in reducing search slopes. In future experiments it would be interesting to change the weights of various factors contributing to the competition in order to examine the effect on search slopes. One might imagine that if the number of times a particular item was probed was manipulated parametrically that search slopes should also change accordingly. For example, if one of two items in a display were probed 5 times as often versus 2 times as often as the other item, search slopes should be shallower in the condition where the discrepancy between the number of times the item was probed was larger.

Recently, several probabilistic models of visual search have been proposed which are based on signal-to-noise ratios across a display (e.g. Eckstein, 1998; Palmer, Verghese, & Pavel, 2000). These models, which weight the relative salience of the target compared to the distractors could be modified to include learned information about the likely location of a target. Eckstein and colleagues (2002, 2004, 2006) have shown that prior responses to targets can be incorporated into future decision making by increasing the weights to locations with more target-relevant features. This is in contrast to a model whereby attention to particular locations alone have their weights varied regardless of target features. In the experiments presented here changes in attentional weighting to locations alone would not be compatible with learning as each location was probed as a target equally often. However, changes in weights based on target-relevant featural information could result in location 1 being given greater weight for item 1 than item 2 and location 2 being given greater weight for item 2 than item 1, as the target relevant features in those locations would best correspond to the particular target likely to occupy that location. It is possible that these weights could be assigned from an egocentric vantage point and, therefore would not preclude the learning of direction vectors.

In addition, there are several of computational models which have been designed to examine visual search processes (e.g. Cave & Wolfe, 1990; Humphreys & Müller, 1993; Koch & Ullman, 1985). Spivey-Knowlton (1996; Spivey 2006) has simulated a competitive model of visual search using a recurrent attractor network which includes both feed forward and feedback loops. His model uses as a jumping off point the theoretical ideas proposed by Desimone and Duncan (1995) in their Biased Competition model. Desimone and Ducan argued that when multiple stimuli are presented such that their representations are at least partially activated simultaneously they compete. The result is that one stimulus is ultimately suppressed and the other becomes more active and wins the competition. This competition can be biased by such top-down factors as instructions, strategy, attention and context (e.g. Awh, Matsukura, & Serences, 2003). Desimone and Duncan investigated their theory by examining small numbers of neurons.

In contrast, Spivey-Knowlton sought to implement a biased competition model at a higher-level and in more generic terms. He began by modeling basic findings in visual search, such as a conjunction search (so called because two different features must be conjoined to detect the target) where one might be asked to detect the conjunction of a red vertical item amongst red horizontal and blue vertical items. This type of search typically results in positive search slopes. In this simple simulation one feature vector would represent the likelihood of each item being the target based solely on its color (red) and the other feature vector would represent the likelihood of each item being the target based solely on its orientation (vertical). Each feature node gets a setting, 0 if the item is not a feature match and 1 if it is a feature match (it is possible to set a node at less than one, but greater than 0 if there is a partial feature match, e.g. pink). The outputs of these vectors are sent to an integration vector which measures the overall likelihood of the item being the target. (The total activation summed over the integration vector is equal to 1.0.) The integration vector cumulates the feedback and sends output back to all the feature vectors. Each feature vector is then assigned a new weight which will be sent to the integration vector on the next cycle. As the competition continues to cycle the integration node corresponding to the target object (red and vertical) increases in activation while the other nodes decrease in activation. When the integration node exceeds activation threshold (set by the modeler) a decision is made. The number of cycles needed to resolve the competition and thus the time to detect the target can be affected by a number of factors. For example, increasing the number of feature vectors (either by increasing the number of items or increasing the number of conjoined features) or the similarity between individual features (e.g. pink vs. red as opposed to red vs. blue) can decrease the initial differences in activation between items at the integration vector leading to an increase in the number of competition cycles needed to reach the activation threshold. Feature searches (e.g. red target among a blue distractor) do not need as many cycles to resolve the competition because regardless of the number of feature vectors dictated by the number of items in the display the difference between red (vector setting 1) and blue (vector setting 0) items at the integration vector is large and thus the activation threshold is reached quickly. In contrast, conjunction searches need more cycles to resolve the competition because the initial difference in activation between the items at the integration vector are small as all items contain at least one target feature (red or vertical), this is further exacerbated as the number of feature vectors increase and the weights assigned at the integration vector are divided among more items.

One might imagine that this type of model could be adjusted to include the probability that a particular item will occur in a particular location or in a particular direction from the start of the search. For example, consider a design like that used in Experiment 3 where each target was assigned a HP and a LP location. Probability feature vectors could get added to the model such that after learning the repeated display a HP location would have a setting of 1, a LP location a setting of .5, and a distractor location a setting of 0. Under these conditions, one would expect that the HP target would be located with fewer competitive cycles than the LP target. Furthermore, you would expect that as the number of target items for a display increased it would take longer for the model to reach threshold activation because more items would factor into the competition at the integration vector. I am currently conducting an experiment investigating the difference in RTs to HP compared to LP locations when four items in the display are probed as targets. It is expected that even if participants can learn the likely locations of four different targets that RTs will be greater when four targets were probed than when only two targets were probed. Finally, given Spivey-Knowlton's (1996) model one can imagine that in Wolfe et al's. (2000) study even if participants learned the likely locations of the target items search slopes would have been positive because as the number of items in the display increased, so did the competition among the items in the display because each items was probed an equal number of times and thus no set of feature vectors were biased by learning.

6.2 Role of Repetition Priming vs. Statistical Learning

Despite the fact that in all of the experiments presented here targets were presented both in random order and equally often, the same target probe could occur with the same display on successive trials. For example, if "N" were probed and located at 12 o'clock over successive trials or if "F" were probed and its target foil "A" was located at 7 o'clock over successive trials. This raises the question whether the effects observed here were due to statistical learning of the likely locations of target items or transient facilitation due to trial-to-trial repetition priming. A number of studies have shown that simple repetitions across target locations can facilitate RTs to those locations (e.g. Hillstrom, 2000; Maljikovic & Nakayama, 1996; Rabbitt, Cumming, & Vyas, 1977; Shaw & Shaw, 1977). Recently, Walthew and Gilchrist (2006) have shown that if repetitions were eliminated in a search task where location probability was manipulated there was no longer an advantage for more probable locations. They presented participants with an eight-item search display in which targets were twice as likely to appear on one side (four locations) of the display as the other. In a “repeats” condition trials were randomized and targets could appear in the same location multiple times while in the “no-repeats” condition no target could appear in the same location within four successive trials. Participants were asked to make a saccade as quickly and accurately as possible. Walthew and Gilchrist found that the proportion of correct first saccades was greater for probable compared to improbable locations in the repeats condition, but not in the no-repeats conditions. There are a couple of reasons why this might be the case. Walthew and Gilchrist only reported the proportion of correct first saccades. It is possible that if a greater number of saccades made to the correct location were included in the proportion learning would be observed in both the repeats and no-repeats conditions. Why might this be the case? It is possible that learning effects are somewhat reduced under conditions in which no repeats are allowed because task set affects participants’ performance. In this case repeats across trials may trigger the system to monitor for regularity differently than if no repeats are observed. Shore & Klein (2000) note in their review on the role of memory in visual search that it is possible that short-lived priming effects contribute to long term memory.

I analyzed the results of Experiment 3 in order to evaluate whether participants were faster on HP than LP locations because of trial-to-trial repetition priming rather than learning the likely location of the target. In Experiment 3, HP trials contained more repeats (16.5%) than LP trials (4.6%). A repeat was defined as successive trials in which both the target probe and the display were identical (see above for examples). When all repeated trials were removed participants were still faster to respond to HP than LP trials, indicating that participants were learning the likely location of the target above and beyond any speeding that might have been due to repetition priming. In addition, Geng & Behrmann (2005) in their studies investigating location probability also ruled out the possibility that their effects were due to repetition priming alone by showing response speeding to repetitions in a particular location were greater for high-probability versus low-probability locations. It is possible that the results reported here and Geng & Behrman's (2005) results show evidence of statistical learning rather that just repetition priming because participants experienced trial-to-trial repeats that alerted the system to the statistical regularity in the displays.

6.3 Perception-Action Approaches to Learning

In Experiment 4, I have presented evidence that information about the direction from fixation to the target is incorporated into memory about the display. For example, a participant learns that a vector, 45° from a particular location, has as its endpoint an "H" on the majority of target present trials. When the starting point of the search task is changed the information provided by this direction vector is no longer valid and thus disrupts the target verification process. I argued that learning the direction of the target from fixation may be one mechanism for learning the likely location of the target. Further I suggested the possibility that it may be the actions taken with respect to the display that allow the direction to the target to get encoded. For example, consider the possibility that participants make an attentional movement (recall, that participants did not routinely make eye movements) to the target location to verify its presence. In as much as attentional movements can be considered a component of action it is possible that these actions to the target are learned and remembered.

The role of action in perception has been the subject of much research; in part because the visual system provides distal perceptual information that helps to direct goal-oriented actions (e.g. Goodale & Milner, 1992). Goodale and Milner have argued for a division of labor in the brain such that the ventral stream primarily processes object information, whereas the dorsal stream mediates sensorimotor transformations to allow visually guided actions upon said objects. Often this work has involved examining the role of reaching behaviors, limb movements, or physical examination of an object on subsequent perception (e.g., Harman, Humphrey, & Goodale; James, Humphrey, & Goodale, 2001; Scherberger, Goodale, & Andersen, 2003) but it can also be defined in terms of the role of eye movements on subsequent perception or actions (e.g. Ballard, Hayhoe, & Pelz, 1995). Eye movement and attentional movements have been shown to be closely related; evidence suggests that eye movements and attentional movements are often coupled (e.g. Deubel & Schneider, 1996; Peterson, Kramer, & Irwin, 2004).

Because it is difficult to directly measure attentional movements, experiments are often designed to necessitate eye movements; as a result there is a fair amount of evidence that saccadic eye movements can be coded into memory. For instance, humans and nonhuman primates have been shown to make eye movements to remembered locations, even when the physical stimulus has been removed from that location (e.g. Funahashi, Bruce, & Goldman-Rakic, 1991; White, Sparks, & Stanford, 1994). Spivey & Geng (2001) showed that when participants were asked to remember a particular feature about an object that had been removed from the display they often made an eye movement to the now empty location the object had previously occupied. It appeared that the spatial position of the absent object was stored not only in a representation that could be accessed by cognitive memory, but also in terms of oculomotor coordinates. This same process could apply to target verification in a repeated search display. When the display is presented memories about it are reactivated and the target verification process is instantiated. It is possible that this process is strategic, and participants prefer to check the remembered target location in order to be certain about their response; checking does not cost participants much in terms of time or cognitive resources. However, it is also possible that a checking process occurs automatically as a result of having made repeated attentional movements to the likely location of the target. Participants may be using eye position and spatial context to facilitate pattern completion (akin to Hebbian learning). Pattern completion refers to the phenomenon that partial information given at retrieval evokes the entire memory because only a subset of the neurons that fired at encoding are able to activate the entire population that were firing together at encoding (e.g. Hebb, 1949). For example, in Spivey and Geng's work (2001) a given eye position combined with the spatial context provided by the objects which remained in the display may have caused enough of the cells to fire that were active during the initial experience complete the entire pattern of activation for that particular experience. However, it is important to recall eye movements were not necessary in the experiments presented here. Therefore, if learning in repeated search displays is relying to some degree on memory for actions taken with respect to the display then attentional movements would have to subserve the same function as eye-movement served in other studies. Given that it is difficult to examine whether participants made an attention movement to a location or simply assigned a greater weight to a given location in these experiments it would be interesting to alter my design to necessitate eye movements and thus examine the role of action under new conditions (see remaining questions below).

6.4 Remaining Questions

The current study raises a few remaining questions. First, in the experiments presented here the context of the search remained largely the same. Only the two/three locations in which targets could occur ever varied in terms of the identity of the item occupying that location; distractor items occupying all other locations remained constant across all the trials. The role of the repeated distractors on this learning was not investigated, which leaves the question: Is the pairing between each distractor item and the location it occupies learned or do participants only learn about probed items? If distractor items were suddenly probed after training with the display would RTs to report target presence or absence decrease at a rate greater than that observed with an entirely new display? Or, consider the following design change to Experiment 3: during a training period one of the distractor items occupies both a HP and a LP location. (The distractor item is not probed during training.) Then at test this distractor is probed; would participants respond to it more quickly if it occupied its HP location than its LP location? If participants do not learn the distractor information then on every trial it should be possible to change the context of the display (vary distractor items) without disrupting the learning of the two target items.

Second, it would also be of interest to change the context of the search to real-world scenes. Search in a real-world scene is guided by our semantic knowledge about the likely location of a target (e.g. Biederman, 1972). Biederman, Mezzanotte, and Rabinowitz (1982) found that when participants were asked to determine whether a cued object was the same or different than an object that had been verbally named they were less accurate and slower when the object violated certain properties such as the probability that a particular object should occur in a particular scene as given by semantic knowledge. For instance, when looking for a knife it would behoove us to check the kitchen before checking the living room because we have knowledge that knives are typically stored in the kitchen. It would be interesting to examine violations of our semantic knowledge in tasks where the probability that an item will occupy a particular location is manipulated (like Experiment 3). For example, a semantic-inconsistent condition in which an object was presented in a location that was unlikely in the real world could be compared to a semantic-consistent condition in which an object was presented in a location that was likely in the real world. In the semantic-inconsistent condition a knife would be located with HP on the couch in the living room and with LP in the drawer in the kitchen. In contrast, in the semantic-consistent condition the knife would be located with HP in the drawer in the kitchen and with LP on the couch in the living room. If learning is affected by semantic knowledge one would expect that the difference between HP and LP locations would be smaller in the semantic-inconsistent condition, indicating less learning than in the semantic-consistent condition. Further, because displays with semantic context are likely to be more complex than those used in the current studies it will be necessary to examine whether the time course of the learning is slowed by the increase in complexity.

Third, the displays used in the present experiments allow participants to locate the target without making an eye movement. If the displays were changed in such a way that eye movements were necessary to locate the target then scan patterns could be examined. This would allow me to answer both methodological questions raised by the current experiments as well as some theoretical questions. For example, I could examine the role of location probability on target verification in Experiment 2. Recall, that for 50% location predictable targets in the three-location condition I did not know if participants always checked the 100% predictable target's location first because that location contained the target more often than the other two locations; examining eye movements would allow me to address that question. Further it would allow for the examination of the strategies participants used during target absent trials. Do participants examine target relevant locations more often or longer than other distractor locations, if so this would provide further evidence that participants learned and expected targets to occur in those locations. In addition, I could investigate the degree to which distractor locations that never contained targets were examined. If a small number of distractor locations were examined (with the majority of time spent examining target locations) this would lend support to the hypothesis that noise from the distractor items occasionally exceeded threshold which resulted in checking some of these locations. Finally, in Experiment 4 I could examine whether actions – made by eye movements—are learned under conditions when they are necessary. This could lend some support to a perception-action theory of learning in a repeated search tasks. For example, if participants were learning to consistently make a saccade in a particular direction, when the location of the fixation cross changed after training you might expected a saccade in the same direction as training much like Spivey and Geng (2001) observed in their study. Even if a saccade is not made in the same direction of training one might observe a saccade which exhibits some signs of error correction. For example, a saccade which initially starts in the direction of training, but then either abruptly changes or subtly curves to reflect the new direction in which the saccade must be made to locate the target.

Finally, one could parametrically manipulate the probability information provided in these displays to examine the sensitivity of this learning system. I found in the experiments presented here that participants were sensitive to a likely target presented with 75% probability compared to an unlikely target presented with 25% probability. It would be interesting to examine how much the difference between the HP and LP conditions could be reduced and still observe learning. For example, could participants learn the likely location of the target if it were only presented in that location 55% of the time compared to 45% of the time? Would learning emerge more slowly under these conditions?

6.5 Conclusions

In four experiments I have demonstrated that participants learn a great deal of information about a repeated search context. Participants learn the location of a particular target, the relative probability with which an item is presented in a location, and the direction from fixation in which the target will be located. I have argued that one way this learning may be instantiated is by incorporating direction vectors into memory. In addition, I have shown that positive search slopes cannot be taken as evidence that search is memory-free. In fact, positive search slopes can arise from competition among remembered information concerning display items.

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